Charging Forward

CTA Bus Electrification Planning Report

February 2022

Chicago Transit Authority

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Letter from CTA President Dorval Carter

Dear Fellow Chicagoans,

For more than a century, public transit has been one of the most sustainable modes of transportation, lessening the environmental footprint of the transportation sector by reducing personal car trips and supporting sustainable land use development. Over the last few years, public transit has gotten ever more environmentally friendly with the emergence of electric buses—which will further reduce health-impacting tailpipe emissions and climate-changing greenhouse gas emissions.

I am proud to present to you *Charging Forward*, the culmination of a comprehensive strategic planning study which sets a course for **full electrification of the Chicago Transit Authority's (CTA) entire bus fleet by 2040.**

CTA has been at the forefront of the shift to electric bus technology since our first two electric buses entered service in 2014, making us one of the first transit agencies in the country to run electric buses in revenue service. Today, we have eight electric buses in service, and 17 more that are being tested for service at our garages—altogether we expect to have 25 electric buses in service by the middle of 2022. To date, CTA has also secured more than $130 million in grant funding to continue expanding our electric bus fleet and installing the needed charging infrastructure.

Electrifying the CTA bus fleet will produce an array of community benefits:

- CTA will lead by example, contributing to cleaner air and less traffic noise. These benefits are especially important in communities that bear an inequitable burden of air pollution today, resulting in higher rates of asthma and other health effects. These are the areas where we are prioritizing our electric bus deployments.
- Public transit already produces less than half the CO_2 emissions that driving does per passenger mile.[1] Converting from a diesel to an electric bus fleet will reduce the greenhouse gas emissions from buses even further.

1 Quantifying Greenhouse Gas Emissions from Transit. American Public Transportation Association, 2018.
An Update on Public Transportation's Impacts on Greenhouse Gas Emissions. Transit Cooperative Research Program, 2021.

- Electric buses are expected to create operational savings and benefits for CTA including fuel cost savings and improved price stability.
- With one of the biggest bus fleets in the nation, CTA's adoption can help drive advances in electric vehicle technology, especially for heavy-duty vehicles.

Equity considerations have been critical priorities as CTA has identified the initial routes and garages for electric buses, leading to early deployments on the South and West Sides of Chicago. The electric buses CTA operates currently are based primarily at Chicago Avenue Garage and operate on route #66 serving Chicago Avenue. Charging infrastructure is also installed at 74th Street Garage to support new electric bus deployments in 2022. The additional grants we have secured are anticipated to fund more electric buses for deployment on route #66, and additional buses and chargers to be deployed at CTA's 103rd Street Garage, where many South Side routes originate.

As proud as I am of the progress we've made, it is clear that we have a long way to go. Our fleet includes more than 1,800 buses that will need to be replaced. They are housed at seven bus garages and served by a heavy maintenance facility—all of which will need to be substantially upgraded and retrofitted with charging infrastructure to make electrification a reality. This is no small undertaking and requires the careful coordination of many interrelated investments.

This report summarizes the findings of key analyses that will inform our strategic direction on major decision points and establishes a practical framework for CTA to advance towards full electrification. It gives us important guidance on which technologies to invest in, where to install charging infrastructure, how to sequence the electrification of garages and routes, and how to ensure that the related facility upgrades are coordinated with other modernization needs to maximize cost effectiveness and overall system reliability. Simply put, this report is the roadmap to our bus future.

With the completion of *Charging Forward*, CTA is well-positioned to compete for funding, advocate for policies, and drive technology advances that will be essential to implement this plan. Electrifying the CTA bus fleet by 2040 is a complex and challenging undertaking, but together – with support from you and other stakeholders, as well as proper funding – it is possible. We are fully committed to reaching this important goal for our city and our region.

Dorval Carter

Glossary of Terms

Electric bus – a bus powered by an onboard battery that drives an electric motor, also called a "battery electric bus." For the purposes of this report, the term does not include buses powered by hydrogen. Note that hydrogen fuel cell buses may also be considered electric buses in some contexts because the fuel cells use hydrogen to generate electricity, which then powers the bus's drivetrain.

Slow charger – an electric bus charger providing less than 250 kilowatts (kW) of power, typically used for charging buses while they are parked overnight at garages.

Fast charger – an electric bus charger providing greater than 250 kW power, which may be used for on-route charging or for quickly charging buses at garages.

On-route charging – the practice of charging electric buses at the endpoint of a route (which may also be called a terminal or layover location) during the time that the bus is scheduled to wait before starting its next trip.

Vehicle block – an assignment of work for a single (non-specific) bus, outlining all trips, both revenue and non-revenue, and any recovery time between those trips. A vehicle block typically starts and ends at a garage, but some have alternate start/end locations.

Standard Bus Equivalent (SBE) – a measure of bus storage capacity, in which a standard 40-foot bus is counted as 1 SBE and an articulated 60-foot bus is counted as 1.5 SBE.

State of Charge (SOC) – the percent of a battery's capacity that remains charged with useable energy; if a vehicle's battery SOC dips below a certain threshold, it is at risk of failing to operate.

Pantograph – a movable mechanical arm located over a bus that is used to convey an electrical connection between a charger and an electric bus so that power can be transferred.

Gantry – an overhead structure that is used to support equipment such as charging pantographs.

Acknowledgments

This study was made possible through the generous support of the Joyce Foundation, and in collaboration with Civic Consulting Alliance. We thank them for their partnership in this process.

The study was conducted by Sam Schwartz Consulting in close consultation with CTA staff.

Timeline of major steps towards CTA bus fleet electrification

2014
CTA's first two all-electric buses enter revenue service.

2018
CTA enters into a new contract for more electric buses and chargers.

2019
- City Council adopts a resolution committing to 100% electrification of CTA's bus fleet by 2040.
- Mayor Lightfoot's transition report endorses an all-electric bus fleet by 2040.

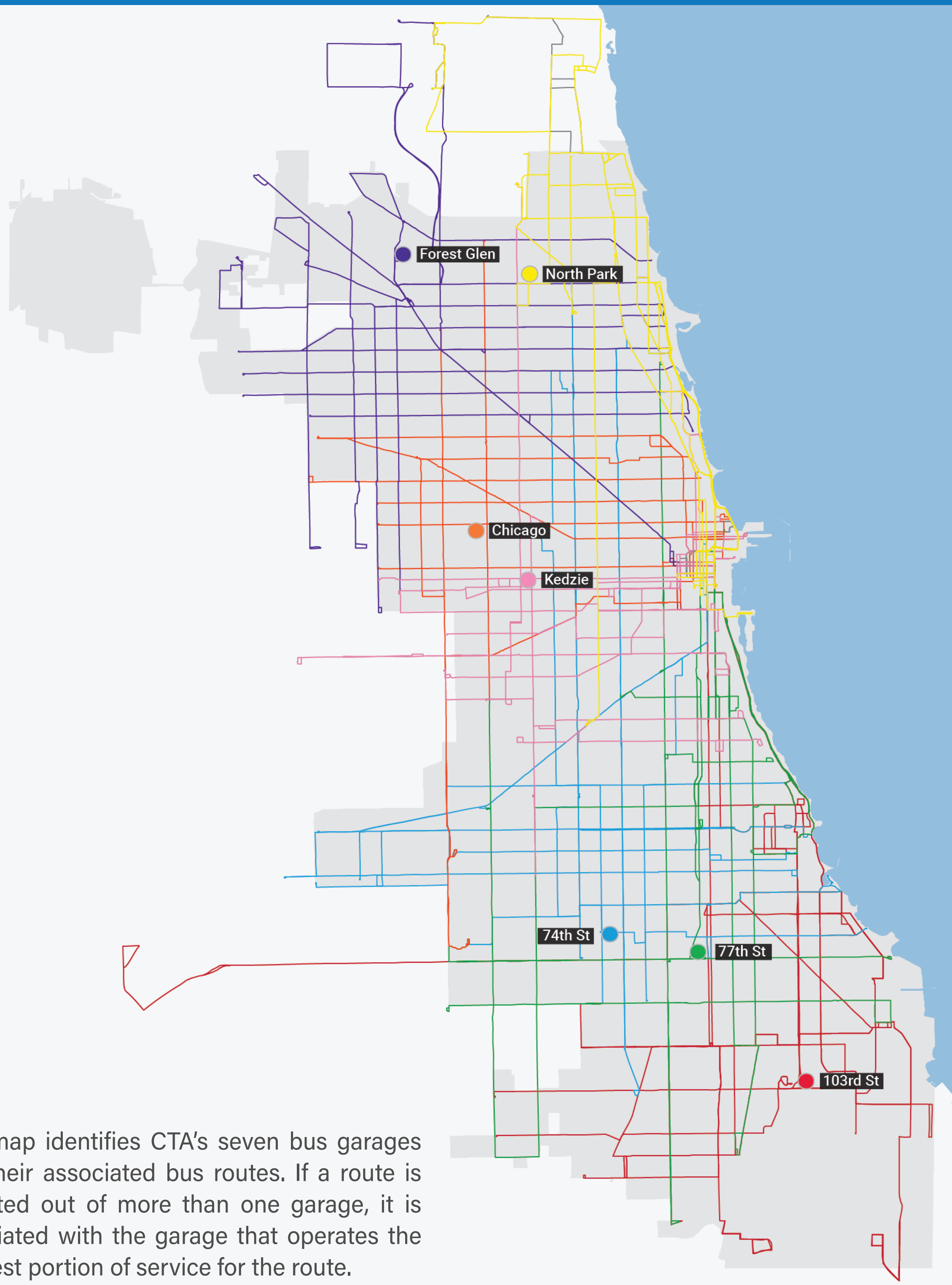
2020
CTA completes installation of its first on-route chargers at Navy Pier and the Chicago/Austin Bus Turnaround.

2021
- CTA launches six new electric buses in service on route #66 Chicago utilizing the new on-route chargers.
- CTA completes installation of one on-route charger at Midway.
- 17 more electric buses delivered; CTA begins testing and preparing them for service.

2022
CTA anticipates having 25 electric buses in service

Figure 1 – Timeline of major steps towards CTA bus fleet electrification to date

Map of CTA Bus Garages and Routes



This map identifies CTA's seven bus garages and their associated bus routes. If a route is operated out of more than one garage, it is associated with the garage that operates the greatest portion of service for the route.

Executive Summary

Charging Forward describes analyses that inform the major decisions that comprise CTA's bus fleet electrification strategy. These include assessments of equity and environmental justice factors, modeling electric bus technology performance with current bus schedules, and testing different approaches to charging buses on-route and at garages. The analyses also include identifying existing infrastructure upgrade needs, projecting costs over the transition timeline, and estimating emissions reductions. The summary-level findings of these analyses are described below.

Equity and Geographic Sequence

Compared to diesel buses, electric buses emit less local air pollution that is harmful to public health, which is particularly important in neighborhoods on Chicago's South and West Sides, where populations with health-related vulnerabilities represent a greater portion of residents and where air quality is often worse.[2] Because of this, CTA plans to prioritize the electrification of bus routes and garages serving these areas. The planned sequencing of garages, shown in the timeline graphic on page 12, places primacy on equity and environmental justice considerations.

Technology Compatibility with CTA Bus Schedules

Modeling of current bus schedules showed that, with the electric bus technology that CTA is already using and a limited network of on-route charging locations, about 66% of CTA's weekday service could be reliably completed by an electric bus. Electric bus technology is rapidly improving, however, so we also modeled different levels of technology improvement, which showed that CTA could reasonably expect to achieve around 88% compatibility for the same schedules based on technology improvement alone. The remaining portion of service would likely require other changes, and the

2 Based on a review of the Chicago Air Quality and Health Index (CAQHI) developed by the Chicago Department of Public Health: www.chicago.gov/city/en/depts/cdph/provdrs/healthy_communities/svcs/air-quality-and-health.html

options for electrifying the longest vehicle blocks[3] have important tradeoffs, discussed further in Chapter 2c.

Locations of Electric Bus Chargers

Analysis of different networks of chargers, with different levels of on-route charging available, concluded that the best approach for CTA is to centralize charging of electric buses at bus garages to the greatest extent feasible, and construct a limited number of on-route chargers at key bus layover locations in order to supplement garage charging and extend the mileage range where most needed.

Garage Charging Technologies and Operations

At garages, buses could charge their batteries either using “slow chargers” where they are parked overnight, or using “fast chargers,” which can charge buses relatively quickly before they are parked for the night, more similar to current diesel fueling operations. Slow chargers would likely take up more space than fast chargers, which could exacerbate existing garage capacity issues. They are also more expensive than fast chargers on a “per bus” basis. However, utilizing more fast charging could require more operational complexity and could require more labor to move buses to and from chargers. Fast charging is also relatively untested on a large scale, and there are concerns that it may lead to faster battery degradation compared to slow charging and might raise reliability issues particularly for electric buses stored outside in cold weather. As a result, this analysis concluded that a mixture of fast charging and slow charging at each garage is likely best, with more fast charging recommended if that technology performs well.

3 Vehicle blocks represent the daily assignment of work for a single (non-specific) vehicle, including all trips, both in-service and out-of-service.

Facility Needs

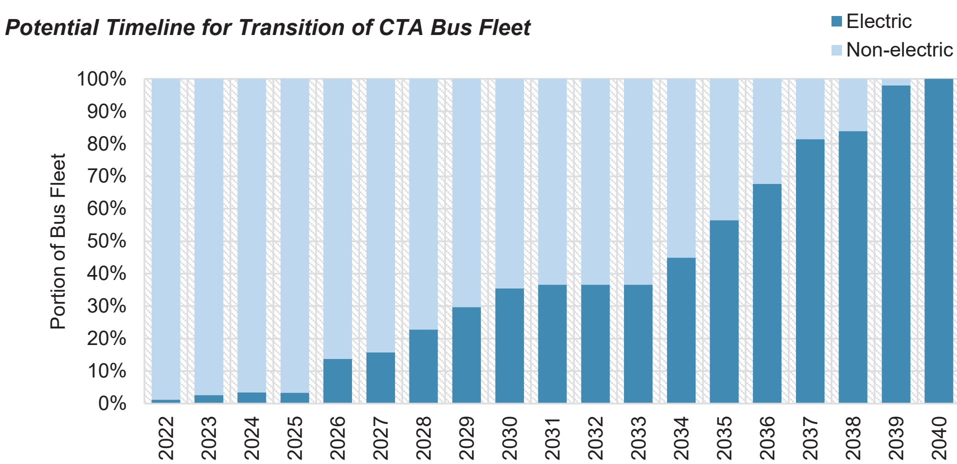
CTA's fleet of more than 1,800 buses is housed and serviced at seven bus garages and one heavy maintenance facility. All eight of these facilities will need new charging infrastructure and other upgrades in order to electrify the full fleet. These investments are every bit as important as the electric vehicles themselves; without sufficient charging infrastructure and the power supply to feed it, electric buses cannot provide service. Many of these facilities also have significant existing state of good repair needs that will need to be addressed or accelerated as part of electrification. New equipment may have physical impacts that trigger code requirements, prompting additional work (such as fire/life safety code). Conditions discovered in the course of implementation may necessitate additional repairs. Other facility upgrades may be advisable in order to help protect the investment in electric infrastructure or efficiently stage work and avoid duplicating effort. For example, if we are installing charger equipment and the surrounding pavement needs replacement, it makes sense to do this at the same time, and any building envelope and roof repairs should be done before or simultaneous to installation of new equipment within garage buildings. CTA's bus garages also already have a significant capacity deficit today, meaning that more buses are currently housed at the garages than they were designed to support. The existing need for an additional bus garage will become more pressing as electrification will likely require more space for charging infrastructure and daily operations. All of these bus facility improvements require careful assessment, planning, design and coordination to ensure they are completed in the appropriate order and avoid major disruptions to daily operations.

"Without sufficient charging infrastructure and the power supply to feed it, electric buses cannot provide service."

Key Components of Electrification Timeline

The specific steps in CTA's electric bus implementation timeline will vary based on the performance and evolution of technology, and the degree to which CTA may need to grow its service over the transition period, but the key features of electrification timelines are common among all the scenarios we developed for further analysis:

- Based on a standard bus lifetime of 14 years, CTA's bus purchases will have to transition to all-electric by 2026 to ensure that the last diesel buses are retired by 2040.
- Facility upgrades will need to be timed to accommodate the number of electric bus purchases planned for each year, and to minimize overlap between the more significant projects.



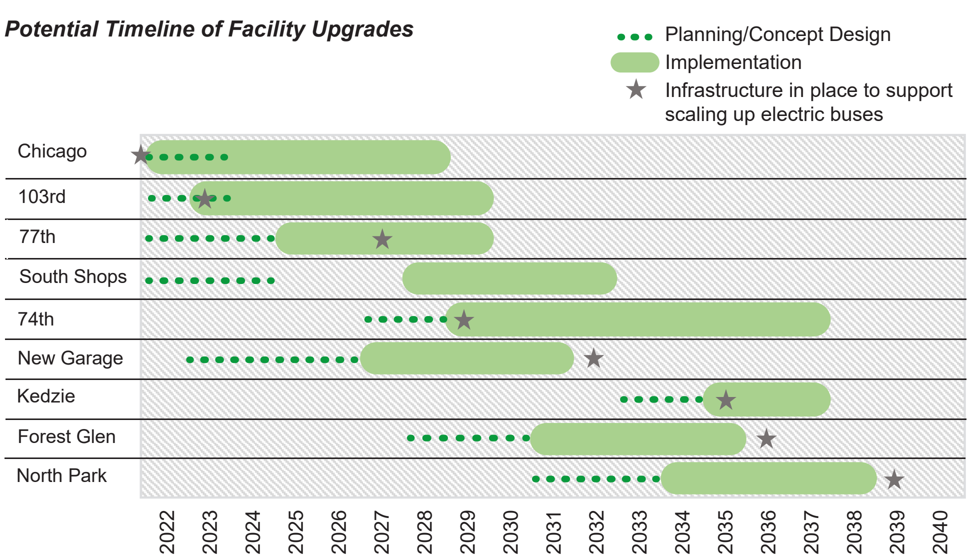


Figure 2 - Example timelines for transitioning the CTA bus fleet and upgrading CTA bus facilities.

- The order in which facilities are upgraded is based on equity considerations and the need to space out major construction projects.
- Continued electrification of Chicago Avenue Garage and partial electrification of 103rd Street Garage are anticipated over the 2022-26 period.
- Significant modernization will likely be required at CTA's oldest bus facilities in order to accommodate bus electrification. The first of these would be at 77th Street Garage, planning for which will need to begin in 2022.
- The later years of the transition would have more sizeable electric bus purchases and facility upgrade needs, including construction of a new garage by 2032 and the significant modernization of two additional garages between 2035 and 2038.

Costs for Bus System Electrification

To help test different mixes of fast and slow charging across different levels of facility investments, eight detailed electrification scenarios were developed and modeled, using our best estimates of the component costs involved. The modeling estimated that converting the fleet to electric buses would require an increase in capital funding over the 2022-2040 transition period of **$1.8 to $3.1 billion on top of the base cost** to maintain the existing bus fleet and facilities, which today is not fully funded. This estimate is based on the following:

- **Increased capital costs to purchase electric buses** include only the incremental cost to purchase an electric bus instead of a diesel bus. This is based on the additional existing cost for an electric bus over a diesel bus, as well as a modest contingency and escalation factors to reflect the year of expenditure. It also assumes that CTA replaces all buses at 14 years as a baseline scenario (which current funding levels have not allowed).
- **New capital costs for electrification of facilities** include installation of fast chargers and slow chargers in the garages and the associated electrical upgrades to the garages (based on the charger scenario). Each facility electrification scenario also includes the same assumption for on-route chargers at 13 locations.
- **Capital costs for state of good repair facility upgrades and modernization are not included** in this estimate of increased capital costs for bus electrification. These costs are discussed more in Chapter 2e, but are challenging to parse with respect to electrification. Some facility upgrades

and modernization will be required for the bus electrification scenarios to be implemented. Other facility needs may be programmed in conjunction with the electrification work to optimize for efficiency, but some may not be required specifically to support electrification. Separate facility-specific analyses are required to identify these needs and will also identify opportunities to program state of good repair needs, in coordination with the CTA's Transit Asset Management Plan targets.

- **Capital costs for a new bus garage are not included** in this estimate of increased capital costs. CTA bus garages already operate over capacity, and electrification scenarios create further strain on available space and operations. A new bus garage is likely to cost an additional **$450 million** beyond the increased capital funding needs identified above.

Electrification is expected to yield operating cost savings due primarily to the lower cost of electricity compared to diesel fuel, which will increase as the electric fleet grows, but these savings will not fully offset the capital investment needed during the transition period.

Our analysis indicates that the 2040 deadline for bus fleet electrification is feasible, but only if CTA can secure significant additional capital funding. The historic average funding of approximately $65 million per year is woefully inadequate to cover the baseline cost for bus replacement at 14 years and does not begin to cover the costs for electrification (vehicles and facilities), the additional garage upgrades and modernization that will be necessary, or the new garage.

While existing electric bus grants can be used to make progress on less complex charger installation and garage electrical upgrades, as well as purchasing additional electric buses, funding for concept design and facility analyses for each of the garages is an urgent near-term need. Each of the garages requires an analysis, and the oldest facilities (77th Street, South Shops, Forest Glen and North Park) will require more extensive modernization plans. Planning, site identification and environmental analysis will need to start within the next two years for the new garage. In addition to near-term planning funds, a reliable funding stream for implementation will be needed to meet the 2040 commitment. This will need to include local and state funding to supplement and match the increased federal funding for competitive Low- and No-Emissions Grants, Congestion Mitigation and Air Quality (CMAQ) Grants, and Bus & Bus Facility State of Good Repair Grants programs.

Environmental Benefits of Bus System Electrification

Finally, we quantified and modeled the environmental benefits of electrification in terms of both the local “tailpipe” emissions and the total emissions inclusive of those occurring at the power generation source. We found that full electrification of CTA’s bus fleet is estimated to reduce total annual CO_2e emissions from CTA buses by 73%,[4] total NO_x emissions by 98%, and local $PM_{2.5}$ emissions by over 99%, compared with maintaining a diesel fleet. It is worth noting that electrification is projected to increase total $PM_{2.5}$ emissions as a result of power generation, but this could be reduced if the mix of power generators on the regional grid shifts toward cleaner energy sources.

Taken together, the results of the *Charging Forward* analyses show that the benefits of electrification will be significant, and also that a great deal of coordination and support from partner agencies and elected officials will be needed to make this ambitious plan a reality.

4 Carbon dioxide equivalent, or CO_2e, is a metric that combines the emissions from various greenhouse gases based on their global warming potential.

Chapter 1. Overview of Electric Bus Technologies

Electric bus technologies have been rapidly improving in recent years, and are expected to continue to do so.[5] CTA's first electric buses, delivered in 2014, have batteries with 300 kilowatt-hours (kWh) of energy capacity. CTA's most recent electric buses have batteries with 440 kWh of energy capacity, and models on the market today have even larger batteries with 660 kWh of energy capacity. Other associated technologies, including charger equipment, have been improving along a similar trajectory. In general, this is good news, but the rapid change also poses a challenge for long-term planning. In order to help manage the uncertainty, we developed several sets of technology assumptions for modeling and analysis purposes.

Technology Assumptions

Assumptions were developed to account for the need for reliable performance, based on reasonable but conservative expectations for technology. Figure 3 below shows the three sets of assumptions that were developed and used throughout our analyses—current technology, moderate improvement, and significant improvement—along with the respective mileage ranges that can be reliably expected from a 40-foot electric bus for each. "Current technology" reflects the technology found in CTA's most recent electric bus purchases; "moderate technology improvement" is newly available on the market, and "significant technology improvement" is likely to be available within the fleet transition period.

Figure 3 – Summary of three sets of technology assumptions that were used for analyses

	Current Technology	Moderate Technology Improvement	Significant Technology Improvement
Nominal battery capacity	440 kWh	660 kWh	880 kWh
Fast charging power	450 kW	600 kW	750 kW
Effective range of 40-foot bus	~62 mi	~93 mi	~124 mi
Effective range of 60-foot bus	~47 mi	~71 mi	~95 mi

Note: "Effective ranges" are given for a fully charged 40-foot bus with midlife battery degradation during winter conditions.

5 *Charging Forward* focuses on battery electric bus technology, but we should note that other emissions-reducing technologies, such as hydrogen fuel cell buses, discussed further on p.19, may also be considered as an additional solution in the long term as technologies and supply chains develop.

All three technology levels incorporate detailed assumptions that can be found in Section B of the Appendix. These include factors that a) reduce the battery capacity to reflect midlife battery degradation and usability limits, b) apply an energy consumption rate that reflects performance during winter conditions, and c) reflect that batteries do not always accept the full power from chargers (particularly at the high and low SOC values). Note that the battery and charger technology assumptions apply to both 40-foot and 60-foot buses, but the mileage range for 60-foot buses is approximately 23% lower due to the higher battery consumption rate needed to power a heavier vehicle.

Charging Solutions

The two standard mechanisms for charging electric buses are plug-in charging and overhead charging. Plug-in charging has been common for small-scale deployments, but it has the disadvantage that staff must manually plug and unplug buses every time charging occurs. In contrast, overhead charging can occur in a largely automated fashion with minimal staff effort required; with this system, a pantograph can descend when a bus is properly positioned to begin charging, as illustrated in Figure 4. Because it is more automated, overhead charging is becoming more common for larger scale deployments and is the most appropriate mechanism for CTA's needs, although some plug-in charging may continue to be used in a limited maintenance function. Overhead charging is already in use for CTA's current electric buses at several on-route and garage locations.

Figure 4 – Photo of pantograph charger at Navy Pier

An additional differentiation between charging technologies involves the speed or power level of the charging. Charging buses can take place with either lower-power "slow chargers," where buses are parked overnight, or with higher-power "fast chargers," where buses charge relatively quickly at on-route locations and/or at the garage before they are parked for the

night, more similar to current diesel fueling operations. While fast chargers on the market today have one dispenser to charge one bus at a time, slow chargers may have multiple dispensers so that multiple buses can draw power from one charger.

Overhead charging can be used for both **slow charging and fast charging**. For our purposes, we will refer to 125-250 kW power as "slow charging," and 450-750 kW power as "fast charging." Based on our assumed battery sizes, a fully depleted battery will take nearly three hours to charge using slow charging, and a little less than one hour using fast charging.[6] These two types of charging are suited to different operational applications, described further in Chapter 2.

Charging operations can also be classified according to whether they occur **at garages or on-route locations**. If the majority of charging can be centralized at garages, charging is planned as part of evening and overnight bus servicing. Garage charging can utilize either slow chargers or fast chargers, and different strategies may be considered based on whether the facility includes indoor climate-controlled storage or an outdoor storage yard. On-route charging can utilize the time that a bus spends at layover locations, which is typically 3-15 minutes. Layover locations are at the end points of routes where additional time is already built into the schedule to allow any late-arriving buses to realign with schedules for their following trip. On-route charging must use fast chargers, as it seeks to transfer as much power as feasible within a relatively short time. Even if most charging takes place at garages, some degree of on-route charging can be valuable to help extend the range of buses that are operating longer vehicle blocks.

6 Charge time estimates are based on the capacity of new batteries, rather than the reduced capacity as batteries degrade over years of use. The time required to fully charge would go down with this reduced capacity, as would the effective range of a fully charged battery, which is accounted for in analyses.

Focus: Hydrogen Fuel Cell Electric Buses

Throughout *Charging Forward*, we use the term "electric bus" to refer to battery electric buses that use batteries that charge from the electric grid. Hydrogen fuel cells can also be used to produce electricity for a bus; these vehicles can be referred to as hydrogen fuel cell electric buses. Like battery electric buses, hydrogen fuel cell electric buses are a technology CTA can consider to eliminate bus tailpipe emissions. They may be beneficial in some contexts because they have greater operating range and lower weight than battery electric buses.

A hydrogen fuel cell electric bus uses hydrogen and oxygen to produce electricity that powers the bus and emits only water vapor. Most use a hybrid system, in which a battery handles all vehicle performance needs and the fuel cell continuously charges the battery to extend the range of the vehicle. The hydrogen fuel for these buses must be stored, compressed, and dispensed using equipment and operations similar to those used for compressed natural gas fueling.

Hydrogen fuel can be produced in various ways, but for hydrogen that does not rely on fossil fuels for production, the primary method is electrolysis. Electrolysis uses an electric current to decompose water into hydrogen and oxygen. Some agencies run electrolysis on-site to produce hydrogen; another option is to have hydrogen delivered by a supplier.

Adoption of hydrogen fuel cell electric buses presents several challenges:

- **Hydrogen fuel requires substantial safety and fire protection retrofits for CTA's repair and refueling facilities.** This would be a major challenge for CTA's older bus facilities.
- **Hydrogen fuel is currently more costly than electricity.** While the price of hydrogen varies across the United States, hydrogen currently costs substantially more than electricity for an equivalent amount of usable energy.
- **The vehicles are currently more costly than battery electric buses.** While both technologies are currently more expensive than diesel buses, hydrogen fuel cell electric buses are typically at least $200,000 more expensive than battery electric buses.
- **Greater industry experience with hydrogen fuel cell electric buses is needed** before CTA could make this technology a large part of its plans. Thus far the technology has only been used for pilot projects in relatively few locations, mostly in California.

Hydrogen fuel cell electric bus technology is a promising technology with particular utility as a range extender that could be a solution for electrifying some of CTA's longest vehicle blocks that require a greater mileage range between charges than may be feasible to achieve with battery electric buses alone. CTA will continue to monitor the development of hydrogen fuel cell electric bus technology, including through site visits to other agencies conducting pilots, and may pilot it at some point.

Chapter 2. Initial Fleet Electrification Analyses

The flow chart in Figure 5 shows the overall study approach. Our first phase of analyses focused on questions related to when bus purchases would need to occur, how the rollout might prioritize and sequence different garages with respect to equity, where charging might occur, and what facility upgrades are needed—these five initial analyses are shown in the left-most column in the flow chart and are summarized in this chapter. The results of these were then used to develop more specific electrification scenarios for additional modeling, described in Chapters 3 and 4.

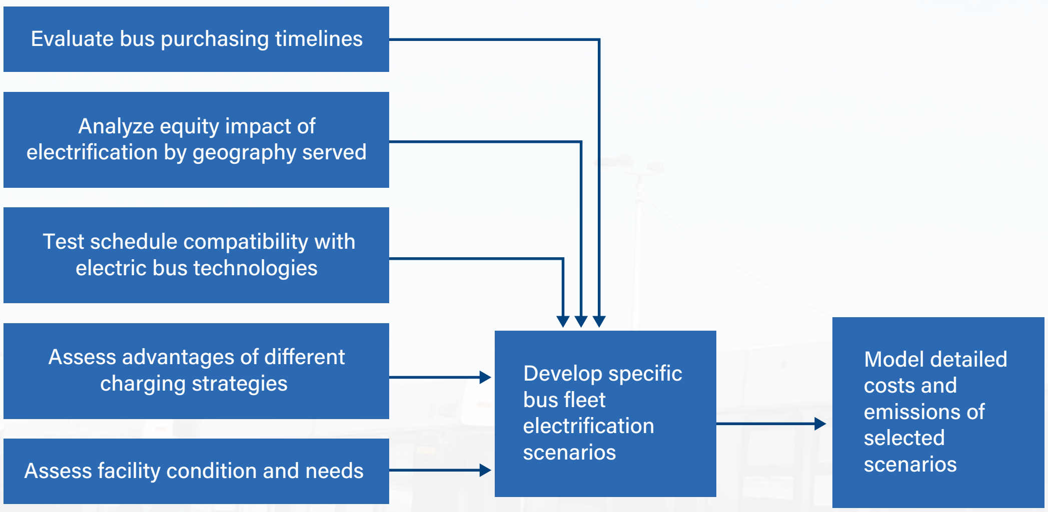


Figure 5 – Flow chart illustrating overall study approach.

2a. Bus Purchasing Timelines

As noted, CTA currently has over 1,800 buses in its fleet. Each CTA bus is expected to have a useful life of 14 years,[7] and purchases of new buses are planned accordingly, so a full turnover of the bus fleet typically takes more than a decade. The 14-year lifetime means that 2026 is the year after which only electric buses can be purchased, in order to meet the 2040 full fleet electrification target date.[8] The graph below shows an example timeline of how the makeup of the CTA bus fleet could change in future years to meet the target of 2040 for full fleet electrification. While we do not show exclusively electric bus purchases beginning until 2026, CTA has already purchased 25 electric buses and plans to purchase more between now and 2026.[9]

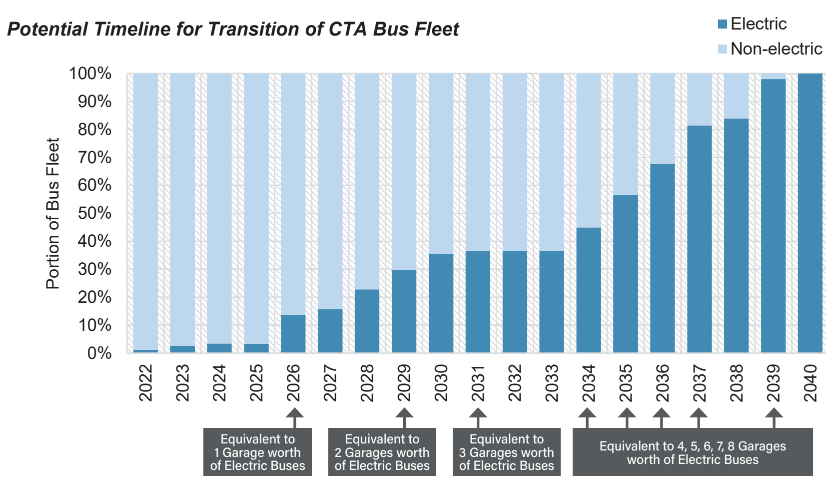


Figure 6 – Graph of potential CTA bus fleet transition timeline. Figures represent purchases that would be needed to replace all buses after 14 years.

The graph also shows that the portion of the bus fleet that CTA replaces is not constant every year, but instead the purchasing schedule is "lumpy" with more purchases concentrated in certain years, and especially towards the end of the transition period. The purchasing schedule determines the magnitude of facilities with charging equipment needed each year to serve the electric bus fleet. The labels at the bottom of the graph show that approximately one garage worth of electrified capacity is needed by 2026, two garages worth of electrified capacity are needed by 2029, and so forth. This is to help give a sense of scale of the charging infrastructure needed at points along the transition timeline; in practice, multiple garages could have mixed electric and diesel fleets throughout the transition.

7 The Federal Transit Administration's minimum requirement is utilization for 12 years based on full depreciation of a standard transit bus.
8 To simplify analysis, we assume that no buses are retired before the end of their useful life and that no buses are kept beyond their useful life.
9 While retrofitting existing buses is possible, and one peer agency is known to be trying this, it is not yet shown to be cost effective, so our scenarios focus on the conversion through purchase of new electric vehicles to replace diesel vehicles as they reach the end of their useful life and are retired.

2b. Equity Analysis

Certain parts of the Chicago region, including many areas with low-income and minority populations, are disproportionately affected by air pollution and associated health issues today.[10] CTA buses constitute a very small percentage of vehicles on the road and contribute a relatively small amount to overall local air pollution.[11] Buses also contribute to cleaner air by reducing the overall number of car trips made, and contribute to equity goals by providing affordable access to residents of all incomes throughout the City. Nonetheless, CTA's current buses are heavy-duty vehicles with large diesel engines that generate air pollution, so one of the primary benefits of CTA's deployment of electric buses is that health-impacting tailpipe emissions from buses would be nearly eliminated. CTA has an opportunity to help address existing inequities by prioritizing bus fleet electrification in these areas, leading by example for other fleet operators. Electrification of our garages in these areas could also help push forward the grid infrastructure upgrades required to support charging, and the improved power infrastructure investment will benefit nearby residents and employers.

Electrifying CTA's bus fleet will reduce local health-impacting emissions from buses by 98% or more. This includes emissions of NO_x, which contribute to respiratory issues including asthma, and emissions of fine particulate matter, which contribute to respiratory issues including chronic obstructive pulmonary disease (COPD) and cardiovascular issues such as heart attacks and strokes.[12]

10 Based on a review of the Chicago Air Quality and Health Index (CAQHI) developed by the Chicago Department of Public Health. More information is available at www.chicago.gov/city/en/depts/cdph/provdrs/healthy_communities/svcs/air-quality-and-health.html

11 On Ashland Avenue (Routes #9 and #X9) and Western Avenue (Routes #49 and #X49), two of the highest bus frequency corridors in the city, CTA buses constitute less than 2% of vehicles daily, based on comparison with IDOT's reported 2018 Average Annual Daily Traffic data for the segment near Madison Street). CTA's garages do not stand out as air quality "hot spots" within their communities, based on a review of Chicago Air Quality and Health Index exposures data. CTA's emissions of particulate matter have been declining sharply over the past decades due to improvements in diesel bus technologies.

12 American Lung Association. What Makes Outdoor Air Unhealthy. www.lung.org/clean-air/outdoors/what-makes-air-unhealthy

The map below illustrates the Chicago Air Quality and Health Index (CAQHI) developed by the Chicago Department of Public Health. This index combines pollution burden and population vulnerability/sensitivity to better reflect the impacts of pollution on each community. The higher scores, indicating a greater burden, are concentrated on Chicago's South and West Sides. This highlights the importance of planning bus fleet electrification to prioritize these communities.

To analyze the potential equity-related impacts of electrification, we first considered two indicators that CTA already utilizes for various evaluations of potential service and fare changes: presence of minority populations, and presence of low-income populations.[13] Analyses of these populations were developed using two approaches: one using the population residing **near each bus garage** within ½ mile, and one using CTA's classification of each garage's **bus routes** that serve minority and low-income populations. (See page 8 for a map of where CTA's bus garages are located, and the routes that are based at each garage.)

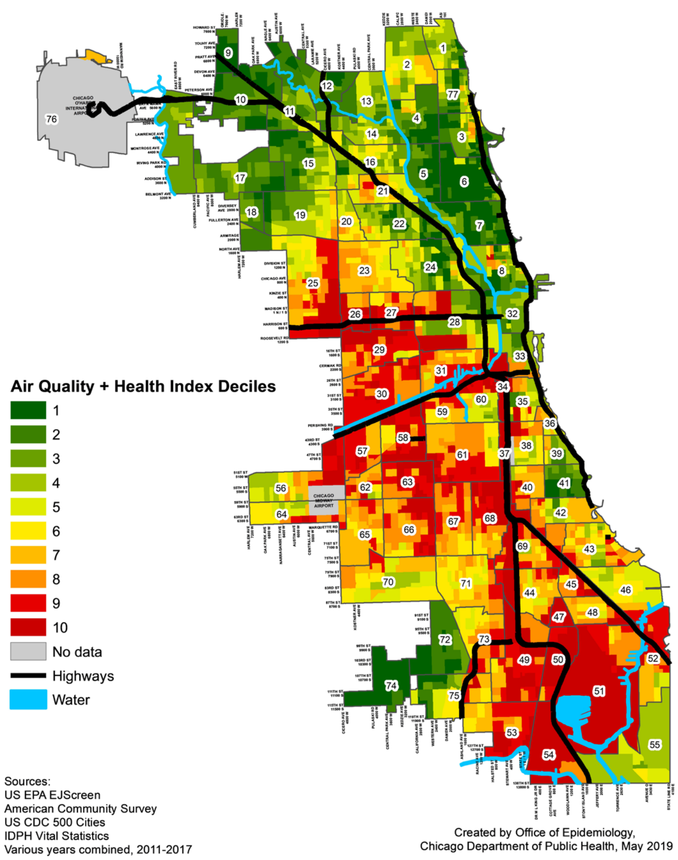


Figure 7 – Map of the CAQHI index throughout Chicago

13 Minority populations must be considered under Title VI of the Civil Rights Act of 1964, and low-income populations must be considered under Executive Order 12898 on Environmental Justice. We focused on the same populations as the federal requirements, but this analysis is not intended to fulfill any reporting requirements. While the federal requirements seek to avoid and mitigate inequitable negative impacts, our analysis went beyond those requirements and sought to prioritize benefits for historically marginalized communities.

A summary of the results of these analyses is shown in Table 1 below. It shows that five of CTA's bus garages serve areas with relatively high proportions of minority and low-income residents, leading to "high" or "very high" classifications with respect to equity-based prioritization. There are not dramatic differences between these five garages. Only two garages have significantly different results leading to classifications as "low" or "medium" priority: North Park Garage and Forest Glen Garage on Chicago's North Side.

Table 1 – Ratings of CTA bus garages based on minority and low-income populations near each garage and its associated routes.

Garage	Prioritization based on proximity to Minority Population		Prioritization based on proximity to Low Income Population		Overall Minority and Low Income Rating
	Near Garages	Near Routes	Near Garages	Near Routes	
Chicago	High	High	High	High	Very High
103rd	High	High	High	High	Very High
77th	High	High	High	High	Very High
74th	High	High	High	High	Very High
Kedzie	High	High	High	High	High
North Park	Medium	Low	Low	Medium	Low
Forest Glen	Low	Low	Low	Low	Low

The different equity indicators are classified in different ways:

- Low income by route and minority population by route: We define low scores to indicate the demographic classification applies to < 30% of routes, Medium is 30 to 50%, High is > 50%.
- Low income near garages: We define low scores indicate the demographic group represents < 20% of the population, Medium is 20 to 35%, High is > 35%.
- Minority population near garages: We define low scores to indicate the demographic group represents < 30% of the population, Medium is 30 to 50%, High is > 50%.
- Overall rating based on average of the four federal indicators, with Very High > 65%.

Following this, a similar supplemental analysis was completed using the Chicago Air Quality and Health Index, which, as described previously, combines pollution burden with population vulnerability/sensitivity.

Table 2 – Ratings of CTA bus garages based on the CAQHI scores near each garage and its associated routes.

Garage	Prioritization based on CAQHI	
	Near Garages	Near Routes
Chicago	High	Medium
103rd	High	High
77th	High	High
74th	High	High
Kedzie	High	Medium
North Park	Low	Low
Forest Glen	Low	Low

CAQHI: Low scores are < 35, Medium is 35 to 55, High is > 55.

The results of this second analysis largely align with the results of the first; both point to a prioritization of the first five garages listed in both Table 1 and Table 2, and among those five all have similarly high priority. These are the CTA bus garages that are located in and serve the communities who need the benefits of electric buses most.

2c. Schedule Compatibility Analysis

As noted in Chapter 1, current electric bus battery technology can conservatively be expected to provide an effective range of approximately 60 miles for a standard 40-foot bus on one full charge. However, many of CTA's current scheduled vehicle blocks are much longer—on weekdays, 19% of blocks are between 100 and 150 miles, and 12% are even longer than 150 miles. Technology is improving, and electric bus ranges are expected to increase, so it is important to compare CTA's current service schedules with both current and improved technology scenarios in order to assess how much bus service can reasonably be expected to be compatible with electric bus technologies by 2040.

The compatibility of CTA bus schedules with electric bus technologies was analyzed through a detailed modeling exercise in order to identify which parts of service may be more challenging to electrify, especially in the near term, and to help guide the rollout of electric buses and chargers to optimize compatibility.

This modeling was completed for every scheduled vehicle block[14] on weekdays and Saturdays from CTA's Fall 2018 service.[15] It was important to model both weekday and Saturday schedules because they have significantly different service profiles: typical service frequencies on weekends are more even across the day, compared to weekdays which typically have significantly more frequent service during the rush-hour peaks. This results in a greater percentage of longer vehicle blocks on weekends. The service profile on Sundays is similar to Saturday, so the model results for Saturday can also be used as a proxy for Sunday.

For both day types, the three different technology assumptions defined in Chapter 1 were modeled: current technology, moderate technology improvement, and significant technology improvement. The modeling also tested two potential networks of on-route charging locations: one limited network with 13 locations, and one more extensive

14 "Vehicle block" is defined as an assignment of work, for a single (non-specific) vehicle, outlining all trips, both revenue and non-revenue, and any recovery time between those trips. A vehicle block typically starts and ends at a garage, but some have alternate start/end locations.

15 These schedules represent the maximum bus service in that year. While there have been some schedule changes since then, these changes should not significantly impact the results. We assume that there will be no impact on public-facing service schedules as a result of electrification.

network with 56 locations.[16] The model reflects that the state of charge (SOC) of each vehicle's battery declines based on the miles operated and increases when on-route charging occurs. If the battery SOC fell below a minimum threshold of 20% at any point, the vehicle block was determined to be incompatible with that technology.

The overall results of this schedule modeling are shown in the table below.

Table 3 – Percent of Fall 2018 vehicle blocks compatible with electrification under different daily schedules, on-route charger networks, and technology levels

Percent of Blocks Compatible with Electrification	No On-Route Charging Locations (Garage Charging Only)		Limited On-Route Charging (13 Locations)		More Extensive On-Route Charging (56 Locations)	
	Weekday Schedule	Saturday Schedule	Weekday Schedule	Saturday Schedule	Weekday Schedule	Saturday Schedule
Current Technology	51%	7%	66%	34%	89%	57%
Moderate Technology Improvement	63%	21%	77%	51%	95%	90%
Significant Technology Improvement	78%	43%	88%	70%	98%	97%

The vehicle blocks that are classified as "incompatible" by the model either have longer mileages to operate, insufficient opportunities to charge on-route, or both. This means that besides adding on-route charging locations, the main strategy to increase compatibility would be to modify vehicle block schedules by splitting them apart into shorter mileage assignments to deliver the same service. For example, instead of one bus making five round-trips on a particular route, it would need to return to the garage after just three trips, and the last two trips would need to be served by a different bus. This approach requires some additional bus operator labor hours, increase to the total miles driven, and may also require some additional vehicles.[17] Other scheduling strategies were also analyzed, such as allocating additional charging time at layover locations with on-route charging. These can also be considered in some cases, but would not be sufficient to make all incompatible blocks compatible.

16 The locations for on-route chargers in these networks were assumed to be existing layover locations and were selected based on site feasibility and the potential need for on-route charging based on schedules; These should be considered model networks only; any future on-route charger locations will be selected based on subsequent and more detailed evaluation, and corresponding rollout of garage-based charging.

17 The potential increase in total miles operated is modest, estimated to be at most 6.2%; this increase does not offset the overall benefits of bus electrification with respect to air quality and climate change.

Several conclusions can be drawn from the results summarized in Table 3:

- Significant percentages of CTA's bus service are already compatible with electrification using current technology. This is true even when just limiting charging locations to garages; more than half of CTA's weekday bus service is compatible using current technology, without any on-route charging locations.
- Predictably, schedule compatibility increases with more on-route charging locations and with more technology improvement. The more extensive on-route charger network makes a significant portion of vehicle blocks compatible if using current technology, but as technology improves, the need for on-route chargers declines.
- Saturday schedules are less compatible than weekday schedules—as noted, this is because Saturday schedules have a larger percentage of longer vehicle blocks. Even with improved technology, Saturday schedules remain more difficult to electrify.
- Technology improvement alone will not make full electrification of current schedules possible, but it can bring us to the point where the necessity of other changes, such as schedule changes or additional on-route locations, is minimized.

While the analysis showed that a more extensive on-route charger network would increase schedule compatibility, there are reasons to be cautious about planning for an extensive on-route charger network. The analysis also showed that the benefit of many on-route locations will decline as technology improves over time, indicating a risk of building excess on-route chargers that become redundant over time. A more extensive on-route charging network would also increase the overall complexity of charger operations, reduce CTA's flexibility to modify bus route terminal locations based on future needs, and create new obligations for CTA maintenance personnel to travel extensively throughout the city. It is also important to keep in mind that even a very robust on-route charger network would still require some garage-based charging. Our analysis showed that if on-route charging was installed at all 78 layover locations deemed feasible systemwide, but no charging at garages was available, around 66% of weekday vehicle blocks and 55% of Saturday vehicle blocks would remain incompatible, even with significantly improved technology.[18] Finally, a preliminary comparison of up-front infrastructure costs and potential long-term operating savings found that there would not likely be any cost advantage to building the more extensive on-route charger network.

18 All current layover locations were evaluated. A location was deemed feasible if it was off-street with sufficient space for at least one charger and associated power cabinets, while still allowing for a passing lane in the case of more than one bus accumulation.

Based on the results of these analyses, CTA recommends the following strategies:

- **Prioritize charging at garages and develop a limited network of on-route chargers.** Centralized charging at garages yields simpler operations, and a significant portion of CTA's bus service can be electrified using garage charging alone. Adding a limited network of on-route chargers, similar in magnitude to the set of 13 on-route charging locations that was modeled, would enhance schedule compatibility without adding excessive cost and complexity.
- **Adapt based on experience and advances in technology.** As technology continues to develop and CTA gains more experience with its performance, CTA will be able to refine recommendations for the locations of the limited on-route charging network in order to achieve full electrification most efficiently and cost effectively. As more is known about future technology performance and we approach the need to electrify the least compatible vehicle blocks, the additional cost and complexity of adding more on-route locations can be weighed against other means of increasing compatibility, such as modifying vehicle schedules.

Focus: Red Line Extension Coordination

When the Red Line Extension (RLE) is implemented, some complementary bus network restructuring will occur to integrate and connect the new rail stations. We used the preliminary plan for the restructured bus network to evaluate impacts on schedule compatibility and the need for on-route charging. While it is not clear that on-route charging will be needed at the new station locations, the plans for RLE stations with adjacent off-street bus facilities are being developed to be forward compatible with potential electric bus charging, to the extent cost-efficient and feasible.

Figure 8 – Map of proposed new Red Line Extension. New stations proposed at Michigan Avenue and 130th Street are anticipated to have off-street facilities for bus connections that could potentially also serve as on-route electric charging locations.

2d. Garage Charging Strategies

As described in Chapter 1, electric buses utilize two main types of chargers:

- Slow chargers add energy to a vehicle's battery at a more gradual rate, and are typically used at the location where the bus is parked overnight, with each bus connected to a charger. Two or three buses can share one slow charger with multiple plug-in or overhead pantograph dispensers, but essentially each bus has its own charging "spot" for the night.
- In contrast, fast chargers come closer to mimicking current diesel fueling operations—a bus pulls up to a charger, recharges for a relatively short time as energy is transferred more quickly, and is then parked elsewhere to be stored overnight so that other buses can use the fast charger.

The time required for a bus to fully charge depends on how depleted the bus's battery is when it begins charging, just like the time it takes to fill an empty fuel tank depends on whether it is partially or completely empty. Today, when a CTA bus returns to its garage after completing its daily trips, it typically spends 15 minutes in a fueling lane, during which time refueling and basic interior cleaning takes place. For electric buses returning to the garage with only a modestly depleted battery, charging at a fast charger could take place within a similar window of time, and simultaneous with routine servicing activities. For electric buses returning to the garage with a more significantly depleted battery, 15 minutes on a fast charger would not be enough to fully recharge.

However, charging a fleet does not have to be done all one way or the other. Different combinations of fast and slow charging are possible, and each method has different advantages and disadvantages. These differences include the number of chargers needed, the cost per charger, the physical space impacts, the peak power draw required, the degree and type of changes to servicing operations needed, and the degree to which the technology has been tested under different conditions. So CTA faces a strategic choice: what mix of fast and slow charging will be most efficient, reliable, and cost effective overall?

Our analysis tested a full spectrum of approaches with the goal of ensuring that each bus is fully charged before it pulls out for its first trip of the day. The results indicate key differences with respect to infrastructure costs, the space needed for chargers, the labor needed for operations, and the peak electrical power draw needed.

"CTA faces a strategic choice: what mix of fast and slow charging will be most efficient, reliable, and cost effective overall?"

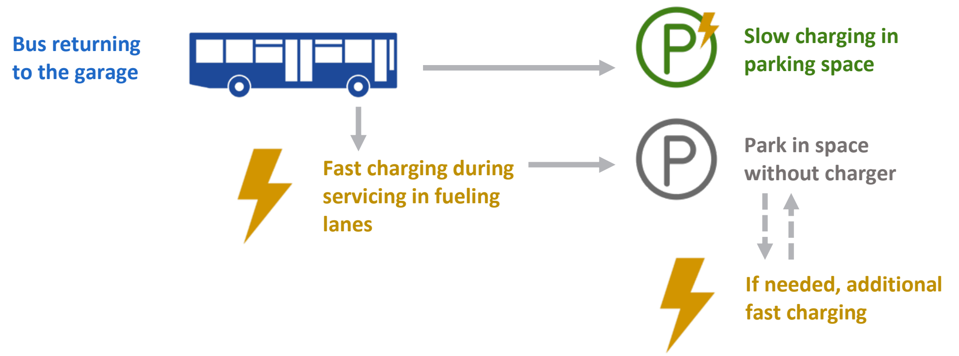


Figure 9 – Conceptual illustration of potential garage charging operations that were evaluated

The graphic in Figure 10 summarizes the range of garage charging strategies that were considered. At one extreme, charging could be achieved with "**All Slow Charging**," defined as slow chargers available for all buses at a garage, in the locations where the buses are parked overnight. This has been a common strategy for many of the initial small-scale electric bus deployments. In practice, at least one fast charger would probably also be installed at each garage for maintenance and resiliency purposes.[19]

19 Note that this charger is not assumed to be used as part of daily scheduled operations, and the analysis of charging and costs reflects this.

For larger scale implementation, it may make sense to install fast chargers at the locations of the current fueling lanes, so that buses have the ability to charge while other servicing activities take place, which would be sufficient for buses that are assigned to shorter vehicle blocks and return to the garage with a relatively high SOC. We therefore defined the second strategy as "**Moderate Fast Charging**," with one fast charger per current fueling lane at each garage and the assumption that each bus could spend 15 minutes at the fast charger during daily bus servicing. In this case, all buses that could not be sufficiently charged in that time would be stored overnight connected to a slow charger.

The third strategy, "**Mostly Fast Charging**," tested a greater amount of fast charging, with two more fast chargers installed at each garage in addition to the one fast charger per fueling lane included in the previous strategy. These additional fast chargers would likely be installed at other locations within each garage, and their use would be prioritized for buses that require a brief "top-off," to reach their target SOC. This approach maximizes usage of the fast chargers and helps reduce the need for slow charger infrastructure. As in the "Moderate Fast Charging" strategy, a sufficient number of slow chargers is included to serve any buses that could not be fully charged using fast chargers in the time available, but the number of slow chargers needed would decline as more buses can complete charging on fast chargers.

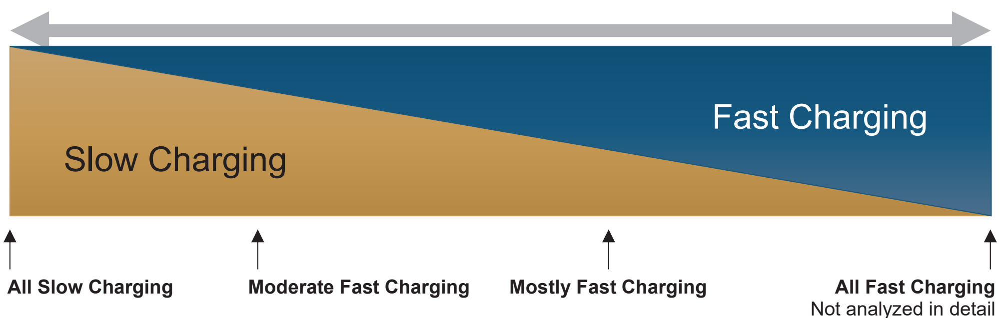


Figure 10 – Different combinations of slow charging and fast charging are possible at garages.

In theory a fourth strategy of "all fast charging" could be considered as well, but this was not analyzed in detail because it would necessitate including some fast chargers that would not be well utilized—they would be needed only to serve a relatively small number of buses every day and therefore be less cost efficient. In addition, having some mix of fast and slow technologies is desirable for the foreseeable future as both technologies will evolve and may perform differently, particularly with respect to battery degradation and extreme temperatures.

These different potential garage charging strategies were analyzed using the results of schedule modeling described in Section 2c, using the limited network of on-route charger locations and assuming that technology aligns with "Moderate Technology Improvement."[20] For vehicle blocks that were found to be compatible with electrification under those assumptions, the amount of charging energy needed was calculated as the difference between the end-of-service SOC and the target SOC expected for buses beginning service. In cases where buses would be stored outdoors and not connected to a charger, the target SOC was set higher, to account for extra energy needed for battery heating during winter conditions.[21] The use of chargers was also scaled up to reflect full fleet electrification, including all vehicle blocks. The analysis was used to estimate the following for each of the three garage charging strategies:

- The number of fast chargers and slow chargers needed, and associated costs of charging equipment. One fast charger costs more than one slow charger, but fast chargers can be shared by more buses every day, and so can be less expensive on a "per bus" basis depending on overall usage.
- The garage's electrical capacity needed, based on peak power draw. Fast chargers use higher power levels, but fewer are generally needed; this results in a lower combined peak power draw. Section C of the Appendix describes the analysis of peak power draw expected based on garage charging strategies; this informs the electrical capacity upgrades needed from ComEd and associated costs.
- Impacts on bus storage space from slow charging equipment, due to the rows of electrical cabinets and overhead gantry footings needed. These impacts were assumed to be smaller at indoor garages, where gantry footings can be aligned with existing columns.[22]
- Additional servicer labor required for any buses that are assumed to need additional fast charging beyond the time they currently spend in fueling lanes, and associated labor cost.

20 The limited network used is the example network of 13 on-route charging locations as discussed in Section 2c. In practice the precise number and locations of on-route chargers may vary based on further analysis.

21 This would apply to fast-charged buses at CTA's two outdoor garages, Forest Glen and North Park.

22 Slow chargers may also reduce operational flexibility, making their impacts larger. Fast charging equipment also takes up space, but we make the assumption that the necessary number of fast chargers can fit within the garage space currently occupied by fueling islands or other space available at the garage.

The table below summarizes results from this analysis for one garage, 74th Street Garage, as an example. It shows that strategies with more slow chargers have relatively high costs for the chargers themselves; as noted, this is because the costs of fast chargers can be more effectively "spread" over many buses. Using more fast chargers also reduces the total peak power needed because, although they draw more power individually than slow chargers, fewer are needed. Having more slow chargers also requires more space, and while the space needed just for equipment itself is estimated to be modest, the fact that CTA's bus garages are already over capacity means that any spatial impacts could be difficult to manage. Finally, the results show that bus servicer labor increases with more fast charging, though the overall costs of the labor are generally modest as well.

Table 4 - Example analysis results from 74th Street Garage.

** "Added Bus Servicer Labor" refers to the staff time that would be needed to conduct fast charging outside of the current standard 15-minute servicing time period.*

Strategy Name	Number of Fast Chargers	Number of Slow Chargers	Charger Costs	Peak Power Draw	Added Bus Servicer Labor*	Additional Bus Space Needed
All Slow Charging	0	83	High	High	Low	Medium
Moderate Fast Charging	5 (one per fuel lane)	53	Medium	Medium	Low	Medium
Mostly Fast Charging	7	9	Low	Low	Medium	Low

Overall, the results suggest that there are a number of advantages to using a significant amount of fast charging at garages. However, there are also concerns about fast charging that may justify caution. Repeated fast charging may cause greater battery degradation over time, and there is relatively little peer agency experience with storing fast-charged buses outdoors in cold climates while not connected to a charger, so it is still unknown how well the bus batteries would perform in these conditions. Based on these considerations, all three garage charging strategies ("All Slow Charging," "Moderate Fast Charging," and "Mostly Fast Charging") were recommended for further evaluation in the next stage of analysis (Chapter 4).

2e. Facility Upgrade Needs

CTA's bus facilities include seven garages, shown on the map on page 8, and one heavy maintenance facility, South Shops, that is co-located with the 77th Street Garage. Charging infrastructure and additional power supply will need to be added to all of these facilities in order to achieve electrification of the full fleet. In addition, due to a chronic lack of sufficient available funding, many of these facilities have significant deferred capital maintenance and modernization needs, some of which will need to be completed to ensure a successful implementation of the conversion to electric buses. Adding new technology that is heavily dependent on integration with existing structural, electrical, and mechanical systems means that facility upgrades that have been deprioritized due to limited funding can no longer be delayed.

It is also important to note that most of CTA's bus garages currently serve and store more buses than they were designed for, which causes operational issues already, and means there is very little flexibility to accommodate installation of new equipment or adjustments to patterns of bus operations and storage. Planning for bus fleet electrification must address these conditions, even though the required upgrades may not be directly tied to electrification.

Facility Assessments

In order to account for the overall facility needs, information was compiled on the upgrades needed for each facility. Associated order-of-magnitude costs were also estimated and compiled to be used in the scenario modeling described in Chapter 4. The following discussion is intended as a high-level overview to identify the types of investments that should be expected; more detailed analysis will be needed to determine all facility-specific improvements and refined costs.

First it should be noted that Forest Glen and North Park are the only two CTA bus garages that currently have all outdoor storage for buses; this feature has implications for electric buses that are discussed in more detail below. Separate from electrification needs, the extent of upgrades needed varies considerably among facilities. Three of CTA's bus garages need significant modernization, which includes replacement of buildings, equipment, and paved areas: 77th Street, Forest Glen, and North Park Garages. The 77th Street Garage is part of a large site that also includes the South Shops heavy maintenance facility; this complex of facilities should be studied as a whole to plan for comprehensive modernization needs. Significant upgrades are needed at 74th Street Garage, including roof replacement, and at 103rd Street Garage, including roof and pavement replacement. Kedzie Avenue and Chicago Avenue Garages have more moderate upgrade needs, such as pavement work and boiler replacement.

Different types of upgrades were classified into two categories, as shown in Table 5 below. Some upgrades, such as charger systems, will be needed specifically for electric buses. Other upgrades also may be essential to complete as part of conversion to electric buses, depending on the conditions of each facility. New equipment may have physical impacts that trigger additional building or fire/life safety code requirements, prompting additional work. Conditions discovered in the course of implementation may necessitate additional repairs. Other facility upgrades may be advisable in order to help protect the investment in charging infrastructure or efficiently stage work and avoid duplicating effort. For example, if gantries for slow chargers are installed throughout a garage's bus storage area, that installation should be planned to occur simultaneously with any needed replacement of pavement and other adjacent infrastructure. Other state of good repair upgrades may be ideally planned to coincide with the upgrades to accommodate electric buses, but would not necessarily be required to achieve electrification. Further study of each facility will be needed to determine which repairs and upgrades must be done to enable electrification, and how best to strategically program them given available funding.

Most of the facility needs listed in Table 5 are the same regardless of charging strategy, although centralizing more charging at garages (versus on-route) predictably increases the need for charging infrastructure at garages, and converting outdoor storage to indoor facilities may be more important for strategies that rely more heavily on fast charging, as discussed more below. Strategies that rely more heavily on slow charging will also likely have a somewhat larger impact on facilities because the physical footprint of the installations would be larger, and so may lead to a greater need for timing other facility upgrades to be simultaneous.

Table 5 – Classification of facility upgrades
Note that these lists are not meant to be exhaustive.

Upgrades that are *needed specifically* for electric buses	**Upgrades that *may be needed* as part of conversion to electric buses, depending on facility condition**
Chargers	**Site improvements** (e.g. concrete/asphalt, drainage)
Charging gantry	**Building structure** (e.g. envelope, roof, doors, etc.)
Electrical infrastructure (transformers, switchgear, housing for equipment, etc.)	**Building systems** (e.g. boilers, HVAC, compressors, exhaust systems, building automation systems)
	Bus maintenance equipment (e.g. bus wash, hoists)
	Conversion from outdoor to indoor storage, if needed

Bus Storage Capacity Needs

As noted earlier, most of CTA's bus garages are currently storing buses in excess of their design capacity. This means that the placement and flow of buses may already be suboptimal, causing operational inefficiencies. It also means that there may be little or no room for additional equipment. Figure 11 below illustrates how the number of buses assigned compares to capacity at each garage.[23] Systemwide, CTA has a bus storage space deficit of over 200 standard bus equivalents (SBE).[24] This situation would likely be exacerbated by electric bus implementation; installation of charging infrastructure and associated new operational requirements is expected to require more space, not less. As a result, the existing shortage of bus storage capacity will need to be addressed as part of the fleet electrification process.

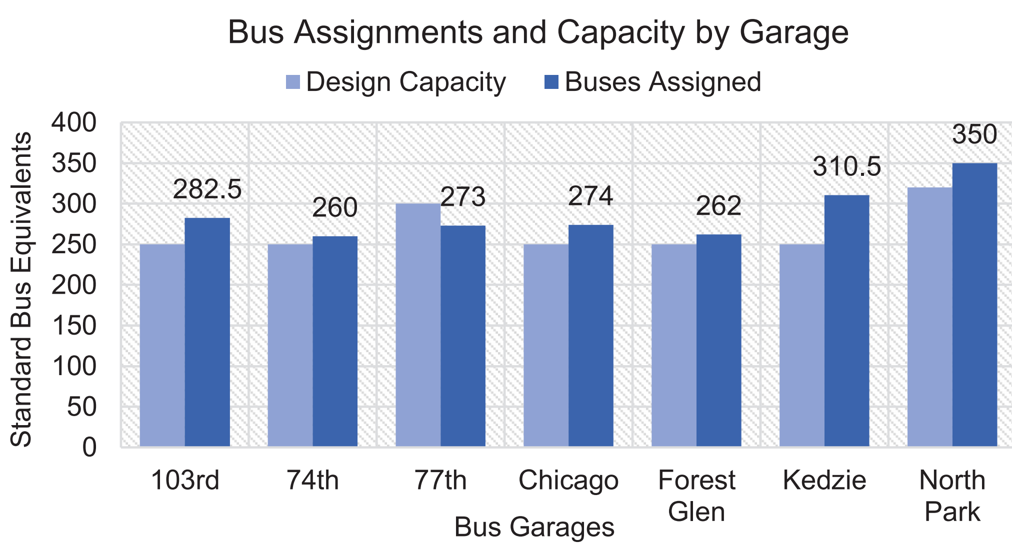


Figure 11 – Graph comparing bus assignments and design capacity at garages
Source: Summer 2019 Fleet Summary

23 Note that this figure represents Summer 2019 conditions. Since then, some buses have been shifted among garages, but overall fleet size and capacity issues remain the same.
24 Bus storage capacity is measured in standard bus equivalents (SBE), in which a standard 40-foot bus is counted as 1 SBE and an articulated 60-foot bus is counted as 1.5 SBE.

CTA has identified three potential projects that could help address bus storage capacity:

- **Identify a site and construct a new additional bus garage.** While a specific location for a new garage has not been selected, the scale of the current storage capacity deficit indicates that a new garage is needed, even before accounting for the increase in storage space needs that may result from electrification. A new garage may also prove critical for temporary use by displaced buses during the construction involved with major upgrades at other garages. For analysis purposes we assume that a new garage could house 250 SBE, which is similar in size to most of CTA's existing garages.
- **Reconfigure Forest Glen Garage utilizing CTA-owned parcels.** CTA owns property adjacent to the existing footprint of the garage facilities; reconfiguring and improving these parcels for garage use could add an estimated 101 SBE of storage. There is an existing need to reconfigure this facility for operational reasons regardless of capacity needs.
- **Reconfigure North Park Garage utilizing CTA-owned parcels.** CTA owns property at North Park that is now used for employee parking. Reconfiguration and improvements to the site could add an estimated 40 SBE of storage.

Electrification scenarios that include a new garage, and variations with respect to reconfigurations at Forest Glen and North Park, were recommended for further evaluation in the next stage of analysis (Chapter 4).

Considerations of Outdoor Storage

Finally, it should be noted that while most of CTA's bus garages store buses indoors with climate control, two of CTA's bus garages, Forest Glen and North Park, currently utilize outdoor bus storage. Outdoor storage can be cost efficient and provide more flexible movement of buses compared to indoor, but it also means buses are subject to the elements and extreme temperatures. Cold temperatures, in particular, have specific implications for electric bus technology, since energy stored in the battery is consumed by electric heaters to keep the battery at an optimal temperature. Therefore, if buses are stored outdoors and not connected to a charger, which would be the standard operation for fast-charged buses, they will need to be charged to a higher SOC before being parked for the night, to accommodate the additional energy needed for battery heating. (Our garage charging analysis, in Section C of the Appendix, factors in this additional energy requirement.)

It should also be noted that during cold weather, CTA's electric buses currently use onboard diesel heaters to heat and maintain interior cabin temperature, and will likely continue to do so for the foreseeable future, although alternative heating technologies are in development.[25] This need will be higher for buses stored outdoors than for buses stored indoors because their starting temperatures will be lower. Diesel buses stored outdoors currently get pre-heated on cold days, so this is not a major difference from current operations. Preliminary analysis showed that the additional costs incurred for battery and cabin heating for buses stored outdoors are far lower than the costs of building and maintaining a new indoor garage. However, adding indoor storage lowers overall risks from weather effects and has other benefits for staff and operations.

Because there are advantages and disadvantages of indoor and outdoor storage with respect to costs and operations, and because the comparison shifts with different mixes of fast and slow charging technology, variations with respect to converting outdoor garages to indoor facilities were recommended for further evaluation in the next stage of analysis (Chapter 4).

Detailed Facility Planning

Conversion of CTA's bus facilities to support electric buses will require additional detailed analysis, planning, and design. Base engineering analysis to model power demand and prepare specifications will be needed to advance future work. Facilities studies will include planning, siting, and environmental analysis for a new garage, and planning for modernization and reconfiguration of 77th Street/South Shops, Forest Glen, and North Park. An important part of studies for existing facilities will be to identify which state of good repair needs must, should, or may not need to coincide with electrification. This work will be coordinated with, and build off of, existing assessments done as part of CTA's Transit Asset Management planning.

Facility planning will need to address strategies for maintaining operations during the transition to electrification, such as fueling, charging, bus flows and staffing needs. It will also be essential to evaluate back-up power solutions, such as onsite power generation and microgrids, to ensure the reliability of garage charging. Continued study will also be needed to refine the locations and sequencing of the proposed limited network of on-route charging locations, and develop detailed designs to integrate the charging equipment at these sites.

25 The use of diesel technology to heat buses means that diesel fuel consumption and associated emissions will not be completely eliminated through electrification in the immediate future. Depending on the charging strategy, annual diesel fuel usage by electric buses is estimated to be 0.2% to 2.2% of the volume that is currently used to power CTA buses. Alternative heating technologies that do not dramatically reduce battery range are in development but are not widely available at this time.

Chapter 3. Defining Detailed Electrification Scenarios

Based on the results of the analyses described in Chapter 2, we reached several key conclusions that informed the next phase of analysis:

- Prioritizing equity considerations means that bus facilities and routes on the South and West Sides of Chicago should be electrified first. This means electrification upgrades should begin first in the five bus garages in these parts of the city.
- Charging operations should be centralized at bus garages to the extent feasible. This should be supplemented with a limited network of on-route charging locations.
- Three different garage charging strategies should be evaluated, defined as All Slow Charging, Moderate Fast Charging, and Mostly Fast Charging.
- CTA's bus facilities have significant state of good repair needs, many of which may need to be coordinated with the conversion to electric buses, especially with respect to the installation of power and charging infrastructure.
- CTA needs a new bus garage to address its existing bus storage capacity deficit and enable electrification. Reconfigurations of Forest Glen Garage and North Park Garage to add more capacity should also be considered.
- While not a prerequisite for conversion to electrification, it may be advantageous to convert CTA's two outdoor bus garages, which are Forest Glen Garage and North Park Garage, to indoor storage.

These findings were used to develop eight bus fleet electrification scenarios, summarized in Table 6. The eight scenarios formed the basis for testing different potential approaches to electrifying CTA's entire bus fleet by 2040 with respect to the operating costs, capital costs, emissions, and garage capacity impacts.[26] For scenarios that include Moderate or Mostly Fast Charging, the variable of whether or not to convert outdoor storage facilities to indoor was also tested, because indoor storage is expected to be particularly advantageous for buses that are fast-charged.

26 All eight scenarios assume the same level of supplementary on-route charging, using the more limited model charger network. They also assume Moderate Technology Improvement and use of vehicle schedule modifications to reach 100% schedule compatibility, which is estimated to generate an increase in operational labor cost and necessitate a slight increase to the bus fleet size.

All eight scenarios assume a new garage to help address existing capacity issues, and all eight scenarios assume that upgrades to existing garages address all state of good repair needs.[27] Variations with respect to whether additional garage reconfigurations take place are also included, but it is important to note that this choice is not directly related to electrification; rather, it is tied to the anticipated level of overall fleet growth over the full transition period, which is uncertain at this point and will be determined by factors other than electrification. (See page 45 for additional discussion.)

Table 6 - Summary of eight fleet conversion scenarios.

Scenario	Fast/Slow Charger Mix at Garages	Is a new garage included?	Reconfigure Forest Glen and North Park?	Convert Outdoor Garages to Indoor?
Scenario 1	All Slow Charging	Yes	No	No
Scenario 2	All Slow Charging	Yes	Yes	No
Scenario 3	Moderate Fast Charging	Yes	No	No
Scenario 4	Moderate Fast Charging	Yes	Yes	No
Scenario 5	Moderate Fast Charging	Yes	Yes	Yes
Scenario 6	Mostly Fast Charging	Yes	No	No
Scenario 7	Mostly Fast Charging	Yes	Yes	No
Scenario 8	Mostly Fast Charging	Yes	Yes	Yes

Timelines and Sequence of Garage Upgrades

The scenario modeling requires defining specific timelines for when bus purchases would occur and when facility improvements would occur. Since the end date for complete conversion is 2040 for all scenarios, these timelines are generally similar, with minor differences to align electric bus purchases to the facilities' available charging and storage capacity. The planned facility improvements are timed to space out significant modernization projects; five years apart if possible. They are also timed to ensure that sufficient charging capacity is always installed and ready to serve the number of electric buses planned for each transition year, as the electric portion of the fleet grows and diesel buses are retired. It is important to note that some garages may not be fully converted for electric buses all at once; but rather be completed in phases.

27 As discussed in Chapter 2e, it may not be essential to meet all state of good repair needs for bus facilities before proceeding with electrification, however it is not possible to determine the division of essential and non-essential upgrades without the additional, more detailed, facility planning studies that have been noted as a critical next step.

All scenarios include upgrading CTA's bus garages in the same sequence, which was determined based on the considerations as follows:

- First, this sequence prioritized equity considerations. The four garages rated as "very high" priority for equity were the first four garages to begin receiving electric buses and charging infrastructure: Chicago Avenue, 103rd Street, 77th Street, and 74th Street.
- Next, the sequence was adjusted to ensure that the major construction projects were paced in a way that is more feasible considering the funding, lead time, other resources, and operational disruption involved. This minimizes overlap between the projects at 77th Street, Forest Glen, and North Park, and the project of constructing a new garage. We also assumed that each of these major projects would take several years of planning and design and therefore the earliest possible placement of a major project was third in sequence (77th Street Garage). The other major construction projects were then timed to minimize overlap.

Table 7 below summarizes these factors and the recommended sequence of garage upgrades. Note that the place within the sequence refers to the timing of the start date for implementation of a first phase of electric buses at the corresponding garage, not the completion date of full conversion of that garage.

Table 7 – Recommended sequencing of bus garages with the factors that were considered

Order	Garage	Equity Prioritization	Facility Upgrades Needed
1	**Chicago**	Very High	Moderate
2	**103rd**	Very High	Significant
3	**77th**	Very High	Major
4	**74th**	Very High	Significant
5	**New Garage**	TBD	New Facility
6	**Kedzie**	High	Moderate
7	**Forest Glen**	Low	Major
8	**North Park**	Low	Major

Figure 12 shows a potential timeline for phasing facility upgrades that would introduce electric buses at each garage following the sequence above. Garages in better condition may be able to support electric buses relatively quickly through incremental upgrades to meet charging requirements; this gives CTA more flexibility in the timing of these garages. However, the garages that need major construction work, including 77th Street, Forest Glen, North Park, and the new garage, may not be able to begin serving electric buses until the projects are complete or mostly complete.

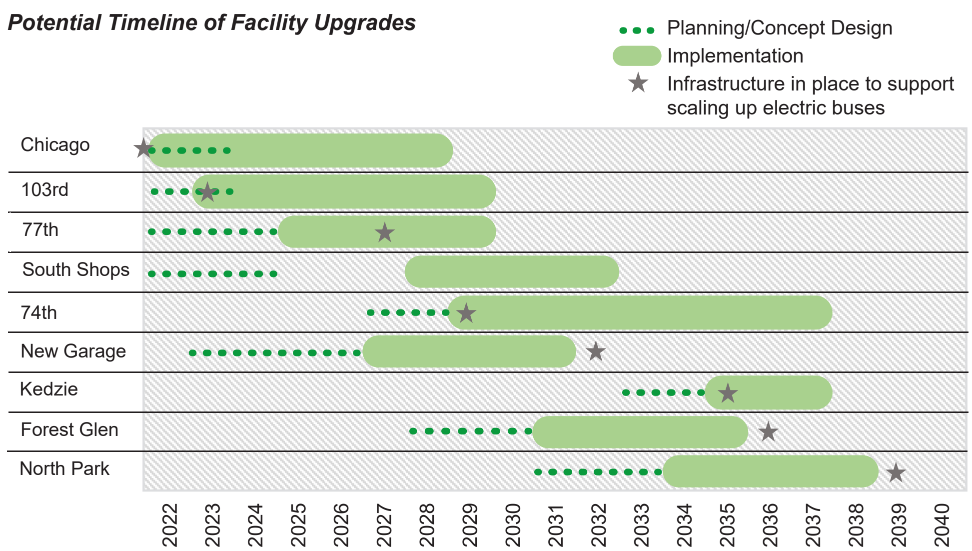


Figure 12 – Potential Timeline of Garage Upgrades. Note that full garage modernization projects are shown as a five-year process that includes planning and design.

Accommodating Fleet Growth

Each of the scenarios is able to accommodate a different level of bus fleet growth, which is a key difference between them. The level of fleet growth that will be needed over the next eighteen years is not fully known at this point (see page 45 for additional discussion), so different scenarios were developed to be able to fit a range of possible needs. Under each scenario, several factors can add or require bus storage capacity, and the resulting balance determines how much fleet growth can be accommodated. These factors include:

1. In all scenarios, it is assumed that space for 32 additional SBE is needed, to accommodate splitting apart long blocks to ensure all service is compatible with electrification.
2. Scenarios using more slow charging are assumed to need somewhat more space for charging equipment, six or seven square feet per slow-charged bus.
3. In all scenarios, it is assumed that a new garage is constructed, adding 250 SBE.
4. Scenarios that include reconfiguration of North Park and Forest Glen assume these changes add more capacity; 40 and 101 SBE respectively. In the scenarios where outdoor storage at these two facilities is converted to indoor storage, the net addition of capacity is lowered to 20 and 81 SBE because of the space needed for new buildings.

Table 8 - Summary of eight fleet conversion scenarios including the fleet growth that can be accommodated.

Scenario	Fleet growth accommodated (SBE over 2021 level)
Scenario 1 All Slow Charging, new garage	-5
Scenario 2 All Slow Charging, new garage, reconfigure outdoor garages	136
Scenario 3 Moderate Fast Charging, new garage	-4
Scenario 4 Moderate Fast Charging, new garage, reconfigure outdoor garages	137
Scenario 5 Moderate Fast Charging, new garage, reconfigure and enclose outdoor garages	99
Scenario 6 Mostly Fast Charging, new garage	3
Scenario 7 Mostly Fast Charging, new garage, reconfigure outdoor garages	144
Scenario 8 Mostly Fast Charging, new garage, reconfigure and enclose outdoor garages	106

Notes: The fleet growth figures are the number of SBE that can be accommodated in addition to the 32 added buses required to split apart long blocks, in order to represent buses that can be utilized for service expansion. A new garage with "Moderate Fast Charging" is assumed to have four fast chargers and with "Mostly Fast Charging" is assumed to have six fast chargers, plus any slow chargers needed to charge the balance.

Table 8 shows the overall potential for accommodating bus fleet growth for each scenario. Three scenarios require keeping the fleet size approximately constant,[28] two scenarios allow approximately 100 SBE of fleet growth, and three scenarios allow approximately 140 SBE of fleet growth.[29]

These eight model scenarios were selected to allow us to identify the range of impacts of different potential strategies, and the relative magnitude of tradeoffs among them. The goal was not to identify one specific "best" scenario that would then constitute CTA's final electrification plan, but rather to better understand the effects of varying possible approaches, in order to inform the key strategic decisions that need to be made at the outset of electrification. Actual implementation may involve a hybrid of components from several of these scenarios, and may be refined based on real world experience as discussed more in Chapter 6, Next Steps.

28 Two of the scenarios show a slight decrease in fleet size, but in practice this can likely be accommodated by slightly adjusting the capacity of the new garage.
29 Because CTA's garages currently store more buses than they were designed for, a similar evaluation of a "current conditions" scenario without a new garage or any reconfigurations would project a deficit of 238 SBE compared to the 2021 level.

Focus: CTA Bus Fleet Size in the Broader Contexts of Climate Change, Equity, and COVID-19

Nationwide and internationally, the last several years have brought new public attention and urgency to the issues of climate change and inequity with respect to race and socioeconomics. Simultaneously, the world has endured and adapted to the onset of the COVID-19 pandemic. All three of these factors have shaped, and will likely continue to shape, individual attitudes and behaviors, politics, and public policy with respect to public transit. This report does not seek to explore all possible ramifications of these forces, but several possible impacts are worth highlighting:

- A greater focus on slowing and reversing **climate change** may increase support for public transit, both in terms of funding levels, supportive policies, and individual attitudes and behavior. It is anticipated that this will lead to increases in public funding specifically for electrification of vehicles of all types, which can reduce climate emissions from the transportation sector significantly, depending on the power sources of the grid that vehicles draw from. Just as important, policies focused on public transit as a key solution to reducing the climate footprint of transportation would seek to shift more trips from low-occupancy vehicles, such as personal cars, to public transit; this would point towards the need for CTA to increase overall service levels and bus fleet size.

- Other sections of this report discuss CTA's intent to prioritize **equity** within the planned sequence of electrification of bus garages and bus routes, in order to reduce health-impacting air pollution in the communities that most need cleaner air. It is also important to note that public transit, and bus service in particular because of its broader geographic coverage, is a critical transportation option for historically marginalized communities. This means that increases to bus service can be a key tool for expanding economic access and improving quality of life for residents and businesses in these areas, and also implies a need for CTA to increase overall service levels and bus fleet size.
- The **COVID-19 pandemic** also has potential implications for bus fleet size and electrification. The pandemic has directly impacted use of public transit, and its lasting effects may continue to do so, in particular with respect to a predicted rise in telecommuting. As in other cities, transit ridership in Chicago fell sharply at the start of the pandemic, although CTA's bus system experienced smaller losses than its rail system. CTA continued to provide hundreds of thousands of bus rides daily, even when stay-at-home-orders were in effect, including commutes for essential workers. Since the Spring of 2020, transit use has risen and fallen at various stages as the city has moved through different phases of reopening and experienced different levels of prevalence of the disease. Since vaccines became widely available, transit ridership has gradually been returning, but it is still unclear what the "new normal" will look like. One possibility is that ridership will largely return, but the traditional AM and PM peak travel hours will be less busy, with ridership spread more evenly throughout the day. If this happens, CTA could modify service in order to reallocate some service from the peak periods to the rest of the day. This type of change would generally lead to longer vehicle blocks that tend to be less compatible with electric bus ranges, but it may also reduce the need to grow the bus fleet with respect to the number of buses needed during peak hours.

Chapter 4. Cost and Emissions Projections of Electrification Scenarios

The final phase of analysis completed for this study was detailed modeling of the eight fleet electrification scenarios presented in Chapter 3, in order to better understand the financial implications of each scenario, and predict emissions of three key air pollutants. This modeling was completed for the entire CTA bus fleet over the period 2022-2040. Table 9 lists the major cost categories and specific types of emissions included in this modeling. More details of the analysis inputs can be found in Section D of the Appendix.

As a baseline for comparison, we also included two diesel fleet scenarios in this modeling. One of these scenarios (D1) represented a no-growth scenario for the fleet while the other scenario (D2) represented a high-growth scenario. Both of these scenarios included the facility state of good repair upgrades and capacity increases that are generally needed regardless of electrification. Scenario D1 included a new garage to address the existing storage capacity deficit, while Scenario D2 included reconfiguration of Forest Glen Garage and North Park Garage in addition to a new garage to accommodate additional fleet growth.

Table 9 – Major cost categories included in cost modeling

Operating Costs	Capital Costs	Emissions
▪ Diesel fuel	▪ Vehicle purchases	▪ CO_2
▪ Electricity*	▪ Vehicle mid-life overhauls	▪ NO_x
▪ Maintenance	▪ Charger infrastructure*	▪ $PM_{2.5}$
▪ Additional bus operator labor*	▪ Facility upgrades and new construction	
▪ Additional servicer labor*	▪ Electrical upgrades*[30]	

** Only applies to electric fleet scenarios.*

30 This includes capital costs for upgrades on CTA's side of the meter and CTA's portion of costs on ComEd's side of the meter, though some of these costs may be covered by ComEd in the future.

Cost Modeling

In addition to better quantifying the tradeoffs among electrification scenarios, the cost modeling produced an estimated range of the total investment that will be required to achieve full electrification of the bus fleet.

When interpreting the results of this modeling, it should be noted that since CTA will need to continue operating some diesel buses throughout the transition period, diesel-related costs decline over time but remain a significant part of overall costs until 2040 when the last of CTA's diesel buses are retired. It is also important to note that the transition-period capital cost projections for electric fleet scenarios are likely higher than the end-state annual capital costs expected from electric fleet scenarios, as the transition period will involve significant facility upgrade costs that are needed to enable the transition. After the transition is complete, ongoing capital investment to update facilities and replace buses and chargers will still be needed, but would be expected to drop off significantly. Unless otherwise noted, the results will be presented in year of expenditure (YOE) dollars, which include future inflation.

Table 10 summarizes the estimated **total operating and capital costs** of the electric and diesel scenarios over the period 2022-2040. It shows that electrification scenarios have lower operating costs compared with diesel scenarios, but they also require greater capital investments during the transition. When operating and capital costs are combined over the 2022-2040 time period, the electric scenarios are projected to be more costly than comparable diesel scenarios by $1.7 to $2.9 billion.[31]

Table 10 – Summary of cost modeling results for the period 2022-2040. All cost figures are in billions of YOE dollars. We define "comparable" scenarios as those that accommodate approximately the same amount of fleet growth.

Scenario	Operating Costs	Capital Costs	Total Costs	Total Cost Above Comparable Diesel
Scenario 1 All Slow Charging, new garage	$3.5	$8.4	$11.9	$2.8 above Diesel 1
Scenario 2 All Slow Charging, new garage, reconfigure outdoor garages	$3.7	$8.9	$12.6	$2.9 above Diesel 2
Scenario 3 Moderate Fast Charging, new garage	$3.5	$8.1	$11.7	$2.5 above Diesel 1
Scenario 4 Moderate Fast Charging, new garage, reconfigure outdoor garages	$3.7	$8.7	$12.4	$2.6 above Diesel 2
Scenario 5 Moderate Fast Charging, new garage, reconfigure and enclose outdoor garages	$3.6	$8.7	$12.4	-
Scenario 6 Mostly Fast Charging, new garage	$3.6	$7.3	$10.9	$1.7 above Diesel 1
Scenario 7 Mostly Fast Charging, new garage, reconfigure outdoor garages	$3.7	$7.8	$11.5	$1.8 above Diesel 2
Scenario 8 Mostly Fast Charging, new garage, reconfigure and enclose outdoor garages	$3.7	$7.8	$11.5	-
Diesel 1 Mostly Fast Charging, new garage, reconfigure outdoor garages	$3.7	$5.5	$9.1	-
Diesel 2 Mostly Fast Charging, new garage, reconfigure and enclose outdoor garages	$3.9	$5.9	$9.8	-

31 We define "comparable" scenarios as those that accommodate approximately the same amount of fleet growth, as specified in Table 10.

Figure 13 presents estimated **annual operating and capital costs** for each year of the transition period, comparing the average results from both diesel scenarios and the average results from all electric scenarios.[32] It shows that operating costs are relatively stable each year for both, but diesel operating costs grow over time, and by 2040, the average results from electric scenarios show an operational savings compared with the average results from diesel scenarios. Capital costs vary more from year to year, and they are greater under the electric scenarios compared with the diesel scenarios, particularly in the second half of the transition period. As noted, for the electric scenarios, capital costs are projected to be lower on an ongoing basis after the transition than during the transition period because the initial facility investments would be complete.

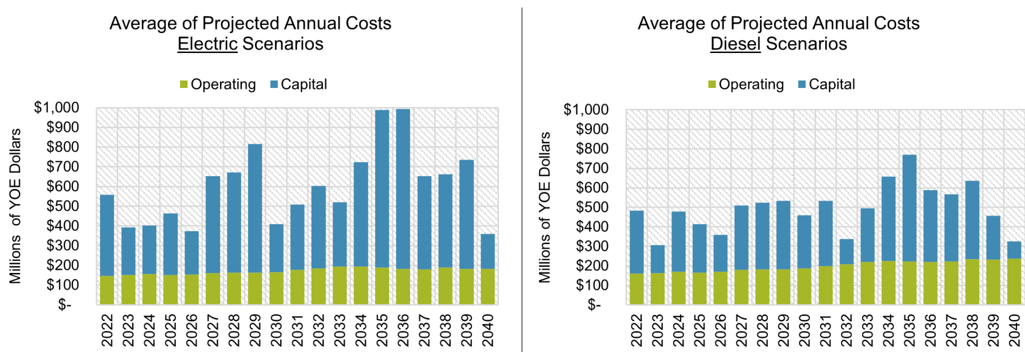


Figure 13 – Projected annual costs comparing average results for electric scenarios (left) and average results for diesel scenarios (right)

32 These annual cost figures represent the average results of the two diesel scenarios and average results of the eight electric scenarios.

Figure 14 summarizes the estimated **2022-2040 capital costs broken out into major categories.** In total, converting the fleet to electric buses would require an increase in capital funding over the transition period of $1.8 to $3.1 billion on top of the base cost to maintain the existing bus fleet and facilities. The electrification scenarios have greater costs related to vehicle purchases, vehicle overhauls, electrical upgrades, and charger infrastructure. The costs related to facility upgrades that relate to state of good repair, modernization, and a new garage do not drive the increased cost of electrification because they are also necessary under diesel scenarios. As noted earlier, CTA bus facilities currently have significant state of good repair needs and operate over capacity.[33]

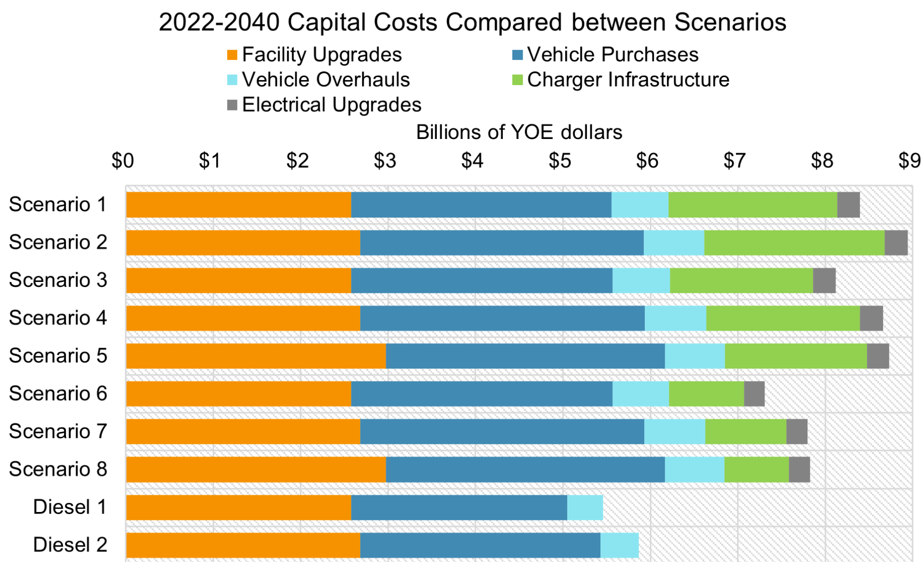


Figure 14 – 2022-2040 Capital costs compared between scenarios

Within the electric scenarios, the more that fast charging is used (versus slow charging), the lower the charger infrastructure costs, and differences in vehicle purchase costs reflect different levels of growth assumed and accommodated by each scenario, not any difference in technology or strategy. Facility upgrade costs are higher under scenarios that accommodate more growth. However, these higher costs to accommodate more growth should be viewed in the context that if they enable an increase in bus service or reliability, this can yield further environmental benefits by attracting more trips that would otherwise be made via personal auto or similar low-occupancy mode.

33 As discussed in Chapter 2e, it may not be essential to meet all state of good repair needs for bus facilities before proceeding with electrification, however it is not possible to determine the division of essential and non-essential upgrades without the additional, more detailed, facility planning studies that have been noted as a critical next step.

Figure 15 shows that the estimated **annual operating costs in 2040**, once fleet conversion has been completed, would be around $25 million lower for an electric bus fleet than a diesel bus fleet. This is due to the lower cost of electricity as a source of energy, compared to diesel.[34] Conventional wisdom holds that electric buses can also yield maintenance cost savings compared to diesel buses, however, longer-term experience operating electric buses is needed to better understand the maintenance cost impacts over the full lifetime of a vehicle. As a result, this analysis uses CTA's experience to date and some additional conservative assumptions regarding electric bus maintenance costs to ensure we are not projecting savings that never materialize.[35]

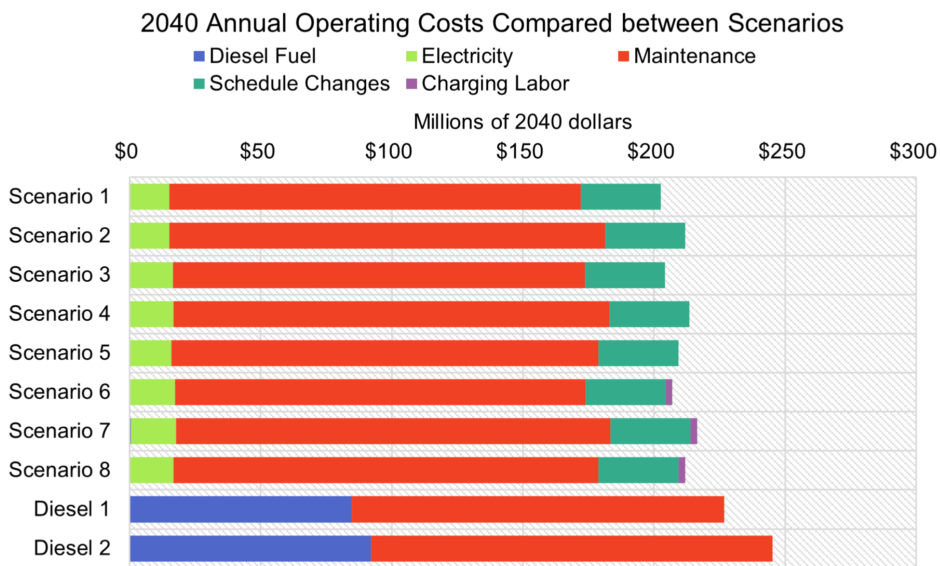


Figure 15 – 2040 Operating costs compared between scenarios
Note that diesel fuel costs for heaters on electric buses are included, but the bar is very small.

34 Note that electric vehicles also tend to be significantly more energy-efficient than internal combustion engines. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. "All-Electric Vehicles." https://www.fueleconomy.gov/feg/evtech.shtml

35 The detailed cost assumptions can be found in Section D of the Appendix.

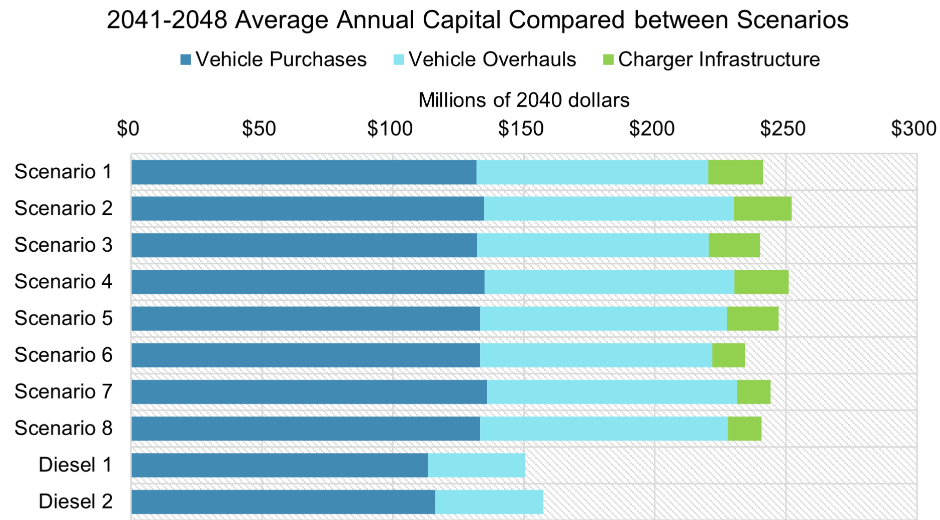


Figure 16 – 2041-2048 Average annual capital costs comparison. An eight-year period is used to account for the annually inconsistent or "lumpy" nature of these costs.

The operating savings from a fully electric fleet is expected to be offset by ongoing capital costs that are reduced compared to the transition period, but continue to be somewhat higher than diesel scenarios even after the transition is complete. Figure 16 shows that the estimated **annual capital costs after full fleet conversion**, over the years 2041-2048, would be around $90 million per year greater for an electric bus fleet than a diesel bus fleet. This is due to the added cost of replacing chargers and the projected higher costs to purchase and overhaul electric buses.

The results of this cost modeling point to several high-level conclusions and tradeoffs:

- Overall, scenarios transitioning to **an electric bus fleet would be $1.7 to $2.9 billion more costly** relative to comparable diesel scenarios, for the combined operating and capital costs evaluated over the 2022-2040 period. The range reflects differences in scenarios with respect to charging strategies and the level of growth accommodated.
- The **up-front capital investment to electrify the fleet is significantly higher** than maintaining a diesel fleet, and ongoing capital costs will remain somewhat higher even after the transition. By the end of the transition, **however, an electric fleet will result in a modest operating cost savings** that is expected to persist.
- **Using more fast charging at garages is projected to be significantly less costly** compared to using more slow charging. However, as discussed in Chapter 2d, concerns remain about the battery performance of fast-charged buses, so **more experience with the technology is needed before fully embracing fast charging** as the primary charging strategy.

- **Converting outdoor garages to indoor facilities adds capital cost but could facilitate more fast charging**, which could generate savings that offset the costs. There are also other benefits of an indoor facility for agency staff and operations.
- **Accommodating higher levels of fleet growth requires higher levels of investment.** The scenarios with the least investment in increased facility capacity (Scenarios 1, 3, and 6) accommodate the least fleet growth, while the other scenarios accommodate greater fleet growth. Fleet growth can bring improvements to the transit system as a whole, but because the level of growth will be determined by other factors, separate from electrification (see page 45), decisions about the appropriate level of fleet growth to plan for, and the associated facility needs, will need to be revisited as trends evolve.

Projected Emissions

Finally, our modeling estimated the air quality and climate change benefits of pursuing an electric fleet strategy compared with a diesel fleet strategy. This analysis considered the local (tailpipe) emissions from buses, and the upstream emissions from generating power used by electric buses. The specific pollutants we analyzed included CO_2e,[36] which contributes to climate change; NO_x, which contributes to respiratory health issues; and $PM_{2.5}$, which contributes to respiratory and cardiovascular health issues.[37]

In addition to the power used by electric buses, some operational factors of electrification will also contribute to local and global emissions; these were included in the modeling and offset some of the reductions. These factors included vehicle block changes, which will require some buses to operate for additional distances to and from garages, using more energy from the grid; and heaters used to warm the cabin temperature during cold weather, which will continue to use diesel fuel and release some local emissions. However, modeling indicated that the impact of these factors is tiny compared with the overall environmental benefits of electrification.

The following graphs illustrate that, relative to the comparable diesel scenarios, the electrification scenarios would reduce total CO_2e emissions from CTA buses by 73% and total NO_x emissions by 98%. These reductions would not be immediate but would develop over time as the bus fleet makeup shifts from diesel to electric. These benefits accrue locally, regionally, and globally.

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36 Carbon dioxide equivalent, or CO_2e, is a metric that combines the emissions from various greenhouse gases based on their global warming potential.

37 American Lung Association. What Makes Outdoor Air Unhealthy. www.lung.org/clean-air/outdoors/what-makes-air-unhealthy

Results for $PM_{2.5}$ show a somewhat different trend. Local $PM_{2.5}$ emissions from CTA buses would drop by over 99%, a clear benefit to Chicagoans. However, total $PM_{2.5}$ emissions would increase by 33%. This is primarily because the electrical grid delivers power generated from fossil-based sources including coal. In addition, newer diesel buses have much lower $PM_{2.5}$ emissions compared to older models, and it is projected that technology improvements will continue to reduce emissions further. It is possible that particulate emissions from electricity generation will decrease in the future as more governments and utilities set targets for cleaner and more sustainable electricity generation.

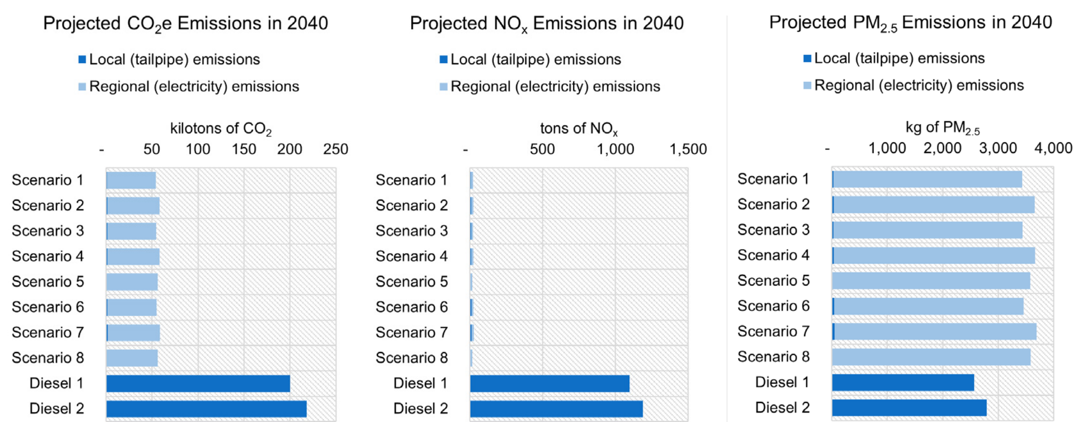


Figure 17 – Projected emissions of three pollutants under diesel scenarios and electrification scenarios

Overall, the reductions in climate-changing emissions and the reductions in local health-impacting emissions are quite significant, and justify the cost increases over the transition period that are summarized in the previous section.

Focus: Grant Funding for Electric Bus Program

Thus far, CTA's electric bus program has received approximately $130 million in funding, primarily through competitive federal grants from the following programs:

- Congestion Mitigation and Air Quality (CMAQ) grants
- Low or No Emissions Vehicle ("Low-No") grants
- Diesel Emissions Reduction Act (DERA) grants
- Illinois EPA "Driving A Cleaner Illinois" VW Settlement grant

All of these programs have additional funds for future grant rounds and will be important sources to support CTA's continued electric bus fleet and charging infrastructure expansion. The recently-passed Infrastructure Investment and Jobs Act also is also expected to provide a significant increase in public transit infrastructure funding compared with previous levels. It includes funding for low and no emissions vehicles and related infrastructure, funding for state of good repair improvements, and greater opportunity for federal highway funds to be transferred to transit projects. These federal programs typically require local matching funds, so the support of state and local partners will remain important.

Chapter 5. Conclusions

Based on the various analyses and findings summarized in this report, CTA has reached several important conclusions related to its electrification approach. These conclusions address the following key strategic questions that must be answered to plan for a transition to an all-electric fleet by 2040:

Is CTA's bus service compatible with electric bus technology?

- **Yes, all of CTA's bus service either already is or can eventually be compatible** with electric bus technology given anticipated technology advances and a reasonable level of adaptation. While many of CTA's buses operate daily distances that exceed the effective range of electric buses on the market today, CTA has several solutions available to address the remaining bus service that is more challenging to electrify.
- With garage charging alone, 63% of weekday vehicle blocks and 21% of Saturday vehicle blocks are already compatible with electric bus technology that is newly available or coming to market soon.
- This means CTA has a lot of service that can be electrified before needing to address the service that is currently incompatible, but CTA will need to assess technology and weigh options for increasing compatibility as the technology develops.
- The primary options to increase compatibility are 1) modifying schedules by splitting apart long vehicle blocks, and 2) adding on-route charging locations. Both of these options add cost and have advantages and disadvantages that should be reevaluated after gaining more experience with the vehicle and charging technologies. It is also possible that service compatibility could be achieved by an accelerated advancement of existing technologies or emergence of new technologies.

How should CTA charge electric buses?

- The best charging mechanism for CTA is **overhead charging using drop-down pantographs.** This is a standardized and automated approach that can be used both for slow charging and fast charging.
- CTA should **centralize charging at garages to the extent feasible**, rather than developing an extensive on-route network of chargers. However, even with technology improvement, it is not likely that all service will be compatible with electrification such that sufficient charging could take place at garages alone. As a result, CTA should also **develop a limited on-route charger network.** These charging installations should be targeted to high-usage locations that benefit a large number of buses that would otherwise not be able to complete their current scheduled service using electric vehicle technology. Minimizing the number of on-route charging locations is important because they require significant infrastructure investment, add complexity and cost to operations, and as technology improves, they will generally become less needed.
- At garages, CTA should **initially implement a "Moderate Fast Charging" strategy**, which includes one fast charger per current fueling lane in addition to slow charging for the balance of charging needed. This choice recognizes that fast charging has the potential to generate significant cost savings, but also hedges against the strategy's potential technology-related risks. CTA can adapt this strategy as it learns from its first garage installations. If fast charging technology and operations work well, and issues such as battery degradation and cold temperature impacts are manageable, then CTA may embrace a "Mostly Fast Charging" strategy to save on capital costs and reduce impacts to storage capacity and overall layout at garages. Conversely, if significant issues emerge related to fast charging, then CTA may choose to shift to more slow charging at garages.

What facility improvements will be needed?

- Upgrades to electrical power infrastructure must be completed to support the amount of charging that will be needed. This includes enhancement and expansion of ComEd's grid infrastructure as well as enhancement and expansion of CTA's own electrical infrastructure at its facilities. Each of CTA's garages is expected to need 5 to 17 MW of additional electrical capacity to support charging, depending on the scenario.

- CTA will need to install a significant number of chargers across its bus garages: The "Moderate Fast Charging" scenario that is recommended initially is estimated to require 500 to 600 slow charger cabinets and 30 to 40 fast chargers in total across all garages.[38] This infrastructure is critical; electric buses without the chargers to support them would be useless.
- CTA's bus garages need various state of good repair improvements that are independent of bus fleet electrification but must be coordinated with electrification upgrades in order to be cost effective and support the new infrastructure. Most significantly, **three garages are in need of significant modernization:** 77th Street Garage, Forest Glen Garage, and North Park Garage. The power upgrades and charging infrastructure required for electrification should be coordinated as part of larger rehabilitation projects.
- South Shops, CTA's heavy maintenance facility for buses located adjacent to 77th Street Garage, also needs significant modernization, as well as the addition of infrastructure to allow servicing of electric buses in parallel with the diesel buses it will need to continue to serve until the full fleet conversion is complete. This facility will be studied together with 77th Street Garage.
- Most of CTA's bus garages currently serve more buses than they were designed for; systemwide, **there is an existing capacity deficit of over 200 standard bus equivalents** (SBE), which is essentially one garage's worth of buses. This causes garage operational issues today and will likely limit CTA's flexibility to accommodate sufficient charger equipment in suitable locations. Operational changes, such as the need to move buses around to charge at different times, may also exacerbate the capacity issues that already exist. As a result, **a new bus garage is needed to provide adequate storage capacity.** This will alleviate current capacity constraints, ensure sufficient space for charging infrastructure, and facilitate bus fleet conversion by providing an alternative base while other garages are under construction.
- Depending on the mix of slow and fast charging that is ultimately pursued and the degree of potential fleet growth that needs to be planned for, there is also a **potential need to increase storage capacity by reconfiguring Forest Glen and North Park garages**, where CTA already owns adjacent properties and has considered reconfigurations.

38 If CTA ultimately shifts to a different garage charging scenario, the number of each type of charger may vary significantly; scenarios with more fast chargers require fewer slow chargers, and vice versa. Based on our analysis, the full variation across all charging strategies systemwide is between 100 and 800 slow charger cabinets, and between 8 and 60 fast chargers. Note that in all cases the slow charger cabinets are assumed to have three pantograph dispensers each, and so be able to serve three parked buses each night.

- Forest Glen and North Park are also the only outdoor garages in CTA's system, and outdoor overnight bus storage may have drawbacks with respect to fast charging in particular. If these facilities are reconfigured to increase capacity, **replacing outdoor storage with indoor storage facilities at Forest Glen and North Park Garages should also be considered.**

How should electrification be phased and organized?

- Based on CTA's standard bus lifetime of 14 years, **bus purchases will have to be all-electric starting in 2026** to ensure that the last diesel buses are retired by 2040. Some phasing in of electric buses before that date has already begun and should continue between now and 2026 to the maximum extent feasible.
- **The sequence of garage upgrades** and construction to support electric buses has been developed based on prioritization of equity and considering the need to avoid overlap of multiple major projects. The planned garage sequence for beginning electric bus implementation and charger installations is as follows: 1) Chicago Avenue Garage, 2) 103rd Street Garage, 3) 77th Street Garage, 4) 74th Street Garage, 5) New Garage, 6) Kedzie Avenue Garage, 7) Forest Glen Garage, 8) North Park Garage.[39] Planning work to address 77th Street Garage and the South Shops heavy maintenance facility and for the new garage must begin soon in order to meet these targets.
- **Sufficient charging capacity must be planned to serve the electric bus purchases anticipated for each year.** Facility upgrades must also be planned to accommodate the need to space out major renovation/construction projects, which require more advance planning and funding, and which necessitate temporary storage for displaced buses. Garages that are currently in better condition may be upgraded incrementally over time to meet growing charging requirements. For CTA's oldest garages that require larger scale upgrades, some facility rehabilitation work may be required in conjunction with the electrification upgrades. In addition to these required upgrades, state of good repair projects should be coordinated with the installation of new infrastructure at bus facilities, whenever feasible, to avoid duplication of effort, construction disruption, and associated cost increases.

39 Note that CTA has already installed a limited number of chargers at several garages to support the electric bus pilots.

What are the benefits of bus fleet electrification?

- Bus electrification will **reduce climate-changing emissions from buses significantly.** Compared to maintaining a diesel fleet, full bus fleet electrification is projected to reduce total annual CO_2e emissions by 73%.
- Bus electrification will **nearly eliminate local health-impacting air pollution from buses.** Compared to maintaining a diesel fleet, full bus fleet electrification is projected to reduce total NO_x emissions by 98%, and local $PM_{2.5}$ emissions are projected to be reduced by over 99%. Overall $PM_{2.5}$ emissions, inclusive of regional and local emissions, are projected to rise by 33% unless the regional grid's mix of power plant fuel sources shifts away from coal and other fossil fuels toward cleaner sources such as wind and solar.
- Although not addressed in detail as part of this study, converting to electric buses also is expected to reduce traffic noise from buses compared with current diesel buses.
- CTA's plans for fleet electrification, and the associated public health benefits, **prioritize improvements in historically disadvantaged communities** including low-income communities and communities of color.
- Pursuing a plan to electrify its sizeable fleet by 2040 will place CTA in **a leadership role**, driving advances in electric vehicle technology, especially for heavy-duty vehicles. It will also enable CTA to share knowledge and experience with other agencies and fleet operators, help catalyze investments in the city's grid infrastructure, and promote vehicle electrification more broadly.
- Electrification is anticipated to generate long-term **operating cost savings** from the lower cost of electricity as compared with diesel fuel. Some maintenance cost savings may be possible as well, but longer-term experience with operating electric buses is needed to confirm the overall impact on maintenance costs.

What resources are needed to achieve full electrification by 2040?

- Meeting the 2040 fleet electrification target will depend on CTA receiving **sufficient and sustained additional capital funding**; electrification cannot be achieved at the expense of service levels or overall system state of good repair.
- The annual capital funding levels necessary to electrify the entire bus system are significantly greater than the historical funding that CTA has received each year over the past decade. Increased annual funding is critical to pay for the higher cost of every electric bus, as well as timely investments in charging infrastructure to ensure that it is installed and fully operational when CTA takes delivery of new electric buses. Increased annual funding will also be needed to cover crucial bus facility upgrades that are most cost-effective and efficient to implement at the same as charging infrastructure installations. Ideally, greater funding levels should enable CTA to adhere to the industry standard of 14 years for the lifetime of a bus – a duration that CTA exceeds today due to lack of sufficient capital funding.
- It is also important for CTA to have a reasonable degree of certainty that recurring funding will be consistent, long-term, and reliably available according to the planned timeline, in order to ensure that phased facility upgrades and charging infrastructure installations are completed efficiently.

"Meeting the 2040 fleet electrification target will depend on CTA receiving sufficient and sustained additional capital funding; electrification cannot be achieved at the expense of service levels or overall system state of good repair."

Chapter 6. Next Steps

This planning study establishes a strategic framework for the electrification of CTA's bus fleet by 2040. Much more work is needed to make this plan a reality. This chapter sets forth several of the critical, specific next steps to begin implementing this plan.

Pursue capital funding and intergovernmental support for electrification. Significant additional capital funding, as detailed in prior sections, will be needed to upgrade bus facilities and purchase electric buses and chargers as part of this plan. In the near-term, additional capital funding is urgently needed to undertake concept design and facility analyses for each of the bus garages; these are crucial threshold steps for the entire 18-year electrification process. This will require substantial support, resources, and coordination from and with many public sector stakeholders, including elected officials and relevant agencies at all levels of government. To the extent that agencies with jurisdiction can provide streamlined or expedited review, permitting, and/or pre-approval processes for electric bus infrastructure, this will help CTA adhere to its schedule for electrification. Coordination with Pace Suburban Bus is ongoing, to ensure that the transitions of both fleets to cleaner vehicle technologies are aligned and efficient.

Conduct outreach to educate, seek feedback, and build consensus around plan elements. This would include outreach to explain CTA's anticipated rollout of electric buses, along with both the benefits of, and challenges to, bus electrification. It would also include more targeted outreach to local community stakeholders and elected officials to seek input regarding the potential local impacts and benefits of garage upgrades or on-route charger installations. These efforts can help CTA refine plans and build support for bus electrification.

Develop detailed facility plans and designs. The results of this study provide a high-level guide to the number and type of chargers and sizing of power infrastructure that will need to be installed to serve a fully electric bus fleet, but more detailed facility-specific planning is required. This includes finer-grained planning and design for each of the seven existing garages and CTA's heavy maintenance facility. It also includes

siting, land acquisition, and environmental analysis for a new garage; finalization of on-route charging locations; and comprehensive planning and concept design for all of these new facilities. At existing garages, this work will include further refined and detailed analyses of electrical loads, exact positioning of chargers and buses within the garages, preparation of specifications, onsite housing for new electrical equipment, and selection of a smart charging management system. Detailed facility analyses will be critical in identifying, at a garage-specific level, the upgrades that are essential to ensure safe, secure, and reliable operation of new charging equipment – such as repairs to roofs, paving, and mechanical systems. It is a particularly high priority for CTA to begin the next phases of planning for the first garages in the transition timeline (Chicago Avenue, 103rd Street, and 77th Street), and to begin the planning process for a new garage.

Continue coordinating with ComEd to design and implement power upgrades. Once the required electrical capacity at bus garages and on-route charging locations is confirmed through in-depth technical studies, CTA should continue working closely with ComEd to complete these upgrades. The timing of these upgrades will be critical as a prerequisite for installing the charging equipment that is required to achieve CTA's broader electrification timeline.

Continue providing additional staff training. While electric buses are not anticipated to dramatically impact staffing needs, there is an ongoing need for additional training for operations, maintenance, and facilities staff on the new technology, as well as some changes to their responsibilities. Bus operators and servicers are already receiving training to drive the electric bus models CTA has in service, properly position buses for overhead charging, and follow electric bus and charger safety protocols. Vehicle maintenance staff and electricians maintaining the new charging infrastructure receive specialized training in topics including bus electrical systems, and diagnostics and troubleshooting. Importantly, training must occur on a recurring basis to ensure that CTA personnel gain knowledge and expertise in the most advanced electric bus and charger technologies that CTA integrates into the fleet and installs at bus facilities. All training, staffing, and position scoping needs have been and will continue to be coordinated with employee unions.

Plan for risk and resiliency. Shifting the source of power for CTA's entire fleet of approximately 1,800 buses brings a host of changes that translate into shifts in risk; for example, the risk of diesel price fluctuations or diesel supply chain interruptions will become less important, but the risk of power outages becomes much more important. Since CTA's rail system has been powered by electricity nearly since its inception, there

is significant agency experience with the associated risks of electric power supply. As exists across CTA's rail system today, CTA plans to ensure back-up power sources are available for charging infrastructure. CTA and other transit agencies are exploring the potential for onsite power generation and microgrids, which could be considered as options for back-up power. Electric buses, like all buses, are tested thoroughly before deployment in regular service. Further analysis is needed to plan for the full array of risks associated with scaling up the electric bus fleet and to develop solutions that ensure resiliency.

Adapt the bus electrification plan based on service levels and funding. The level of need for fleet growth over the transition period will become clearer over time and should inform refinements to the plan. Additionally, if the funding needs described in this report are not met, whether in terms of timing or magnitude, the bus fleet electrification plan and associated timelines – especially for bus facility upgrades – will also need to be adapted to fit the available funding.

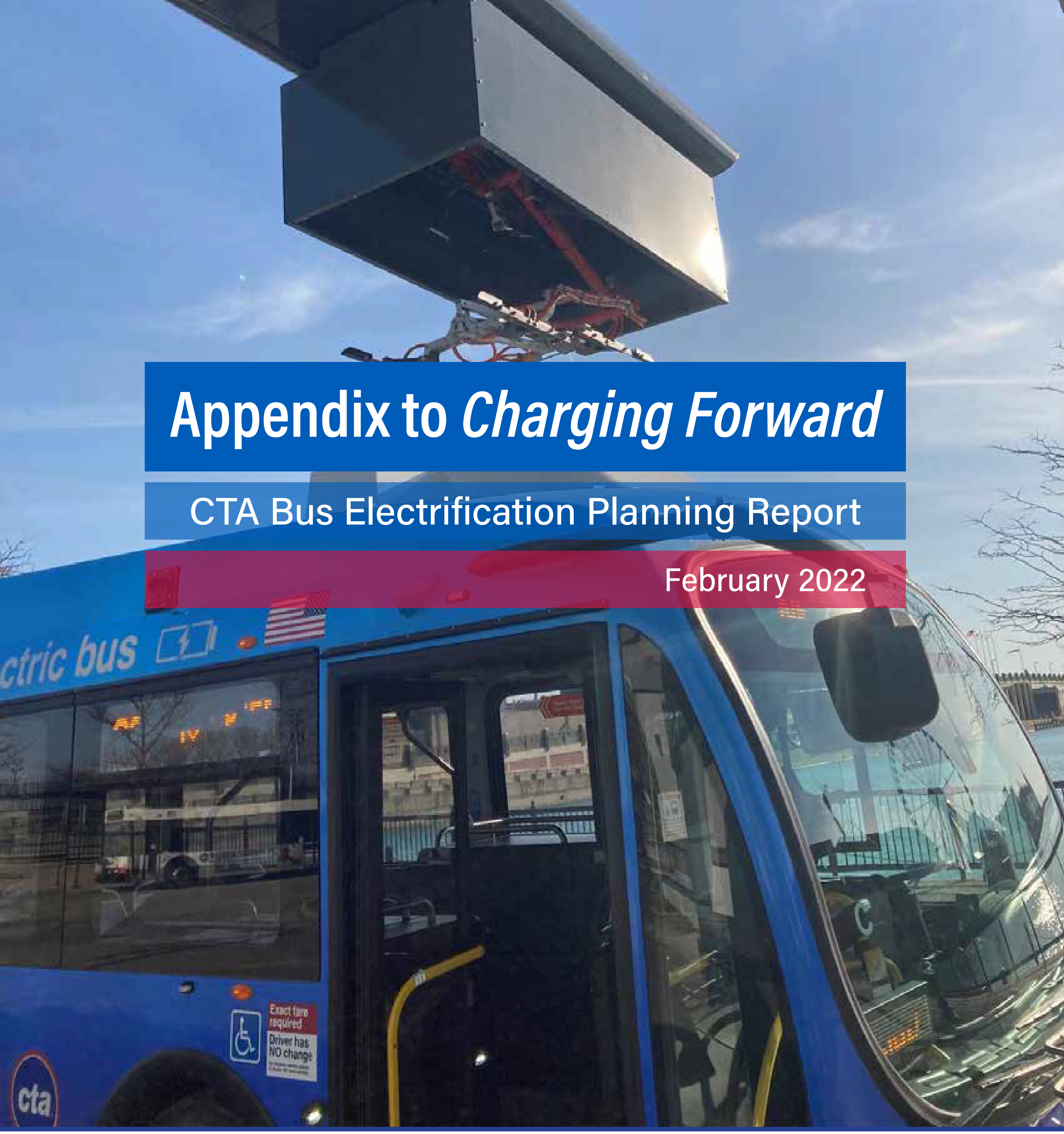
Monitor the performance of technology and refine plans accordingly. The analyses in this plan use the best data available on the performance of electric bus technologies. However, as CTA and other transit agencies gain more real-world experience with electric buses and chargers, plans should be re-assessed and modified as necessary. For example, if the practical range of electric buses is demonstrated to be longer than we have assumed, electric buses may be able to serve longer vehicle blocks than shown in our current analysis. As noted elsewhere, close attention should also be given to the impacts of fast charging related to battery degradation and the performance of outdoor-stored buses. CTA will also monitor the evolution of other emissions-reducing transit technologies, such as hydrogen fuel cell buses, to consider whether and how these play a role in achieving bus system emissions reductions.

The *Charging Forward* study has allowed us to evaluate a range of potential electrification strategies, yielding insights that will be invaluable as we develop more specific plans and projects that advance our bus fleet towards full electrification. CTA is eager to ramp up our deployment of electric buses while continuing to refine aspects of our electrification strategy. We look forward to working together with partners and stakeholders to make this plan a reality.

Appendix to *Charging Forward*

CTA Bus Electrification Planning Report

February 2022



Chicago Transit Authority

This appendix serves to provide additional information about the assumptions, methodology, modeling inputs, and results of the analyses used to develop this report as follows:

- Section A describes the equity analysis that supports Chapter 2b of the main report
- Section B describes the schedule modeling that supports Chapter 2c of the main report
- Section C describes the garage charging analysis that supports Chapter 2d of the main report.
- Section D describes the cost modeling inputs that support Chapter 4 of the main report.

A. Detailed Results of the Equity Analysis

Analysis considering minority populations and low-income populations

We first considered two indicators that CTA already utilizes for other evaluations: presence of minority populations, and presence of low-income populations. Analyses of these populations were developed using two approaches: one using the population residing **near each bus garage** (within ½ mile), and one using CTA's classification of each garage's **bus routes** that serve minority and low-income populations.

First, Table 1 shows the share of the population that is minority or low-income within ½ mile of CTA bus garages. This was determined using data from the Census Bureau's 2017 American Community Survey five-year estimates at the block group geographic level. Minority is defined as non-white, and low-income is defined as earning less than the poverty level. The results show that some garages are in areas with quite high minority and low-income population percentages.

*Table 1 - Results based on the population residing in the area within ½ mile of **each garage.***

Garage	Percent Minority	Percent Low-Income
103rd	86%	41%
74th	98%	27%
77th	98%	40%
Chicago	93%	37%
Forest Glen	19%	6%
Kedzie	95%	45%
North Park	41%	19%

Table 2 shows the analysis based on the classification of each garage's bus routes. For federal reporting, CTA classifies a bus route as serving minority and/or low-income populations if one-third of its total revenue mileage is in census blocks that have a minority or below-poverty-level population percentage that exceeds the minority or below-poverty-level population percentage for CTA's service area. Findings are generally similar to the analysis of the area surrounding each bus garage (illustrated in Table 1 above). Some garages have as many as 93% of routes classified as minority or as many as 88% of routes classified as low-income.

*Table 2 - Results based on CTA classification of the **bus routes** operated by each garage.*

Garage	Percent Minority Routes	Percent Low-Income Routes
103rd	92%	88%
74th	84%	68%
77th	76%	76%
Chicago	93%	86%
Forest Glen	26%	11%
Kedzie	56%	56%
North Park	16%	37%

Analysis considering the Chicago Air Quality and Health Index

Our analysis used the CAQHI, developed by the Chicago Department of Public Health, as a supplemental metric to the federal indicators of minority and low-income populations.

The CAQHI results are summarized in a similar manner to the minority and low-income results discussed in the previous section. Table 4 shows results for the areas **near each bus garage** (within ½ mile), while Table 5 shows results for the area **near the bus routes** operated by each garage (within ¼ mile). The results are also broken down for the four subcategories that make up the index: Sensitive Populations, Vulnerable Populations, Environmental Exposures, and Environmental Effects. These subcategories are defined in Table 3.

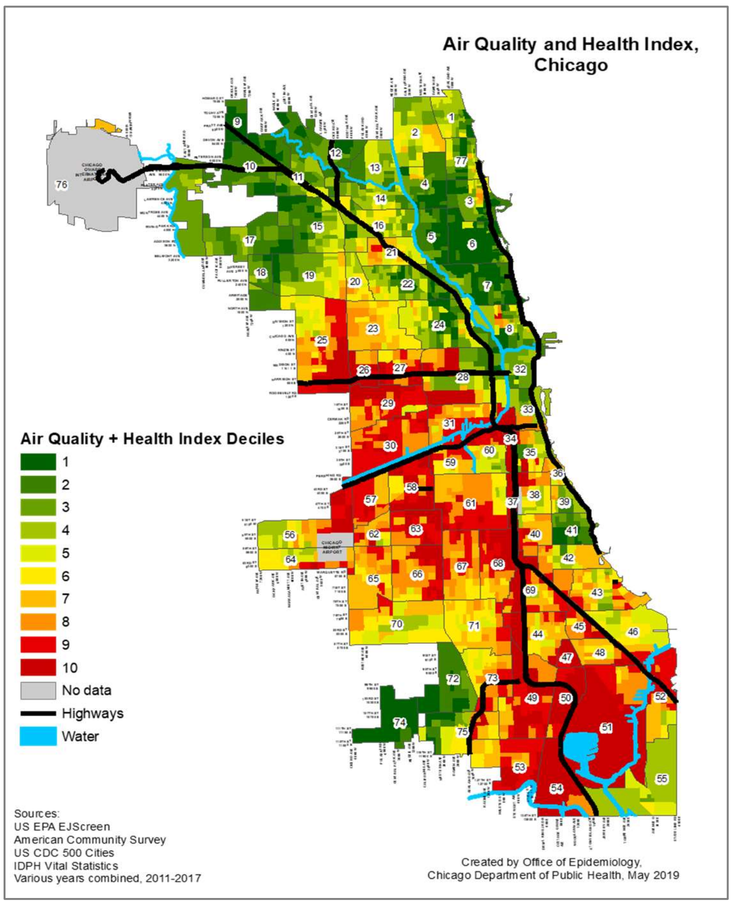


Figure 1 – Map of overall Chicago Air Quality and Health Index

Table 3 – Definition of the specific variables that make up the CAQHI. The variables fall within four subcategories of Sensitive Populations, Vulnerable Populations, Environmental Exposures, and Environmental Effects.

Pollution Burden	Population Characteristics
Environmental Exposures • Particulate matter • Ozone • Diesel particulate • Air toxics cancer risk • Air toxics respiratory hazard index • Traffic proximity and volume	**Vulnerable Populations** • Poverty/income • Race/ethnicity • Education • Linguistic isolation • Unemployment • Housing-burdened low-income population
Environmental Effects • Proximity to risk management plan sites • Proximity to hazardous waste facilities • Proximity to National Priorities List sites	**Sensitive Populations** • Young/old age • Chronic obstructive pulmonary disease • Coronary heart disease • Asthma • Low birth weight

*Table 4 - **CAQHI Results** based on the population residing in the area within ½ mile of **each garage**. Note that higher scores indicate higher burden or vulnerability.*

Garage	Overall Index Score	Sensitive Populations	Vulnerable Populations	Environmental Exposures	Environmental Effects
103rd	94	76	66	50	76
74th	65	76	68	40	47
77th	84	75	68	54	48
Chicago	74	78	76	35	59
Forest Glen	23	50	33	43	35
Kedzie	85	76	71	44	65
North Park	31	40	45	47	37

*Table 5 - **CAQHI Results** based on the population residing in the area within ¼ mile of the **bus routes** operated by each garage. Note that higher scores indicate higher burden or vulnerability.*

Garage	Overall Index Score	Sensitive Populations	Vulnerable Populations	Environmental Exposures	Environmental Effects
103rd	58	61	55	48	54
74th	57	52	55	51	58
77th	58	55	55	51	56
Chicago	48	46	50	54	57
Forest Glen	26	38	39	52	36
Kedzie	50	44	50	56	55
North Park	32	36	38	58	44

B. Detailed Assumptions for Schedule Modeling

Schedule modeling was completed to test the compatibility of CTA bus schedules with various electric bus technologies. This analysis was completed for weekdays and Saturdays using schedules from CTA's Fall 2018 service, which represents the maximum service in that year.

First, the **technology options** to be analyzed were selected. These technologies included 40 ft and 60 ft buses under current technology, moderate technology improvement, and significant technology improvement. Each technology option was given attributes including a usable battery capacity, a battery consumption rate per mile, and a charging power level. These assumptions were selected to represent reasonably adverse conditions, based on CTA experience during winter conditions and including battery degradation over time. (Note that different battery consumption rate inputs are used elsewhere when seeking to represent average annual conditions for cost modeling.) The details of the technology options for schedule modeling are shown in the tables below.

Table 6 – Technology assumptions for 40 ft electric buses. Sources: CTA Bus Engineering and various OEMs.

	Current technology (matches CTA experience and reliable performance in adverse conditions)	**Moderate technology improvement**	**Significant technology improvement**
Buses and chargers	Battery capacity: – Nominal 440 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 282 kWh Battery consumption rate: 3.18 kWh/mi Fast charging power level: 450 kW Slow charging power level: 125 kW	Battery capacity: – Nominal 660 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 422 kWh Battery consumption rate: 3.18 kWh/mi Fast charging power level: 600 kW Slow charging power level: 188 kW	Battery capacity: – Nominal 880 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 563 kWh Battery consumption rate: 3.18 kWh/mi Fast charging power level: 750 kW Slow charging power level: 250 kW

Table 7 – Technology assumptions for 60 ft electric buses. Sources: CTA Bus Engineering and various OEMs.

	Current technology (peer agency experience and reliable performance in adverse conditions)	**Moderate technology improvement**	**Significant technology improvement**
Buses and chargers	Battery capacity: – Nominal 440 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 282 kWh Battery consumption rate: 4.17 kWh/mi Fast charging power level: 450 kW Slow charging power level: 125 kW	Battery capacity: – Nominal 660 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 422 kWh Battery consumption rate: 4.17 kWh/mi Fast charging power level: 600 kW Slow charging power level: 188 kW	Battery capacity: – Nominal 880 kWh – Reduce 20% for battery usability and 20% for midlife degradation – Adjusted 563 kWh Battery consumption rate: 4.17 kWh/mi Fast charging power level: 750 kW Slow charging power level: 250 kW

The core of our schedule analysis is a **simulation of each vehicle block**[1] to test whether a particular technology option would be suitable to complete the scheduled service miles. The state of charge (SOC) of the vehicle's battery is modeled to decline based on distance traveled and to increase when on-route charging occurs. If the battery SOC falls below a minimum threshold, the vehicle block is determined to be incompatible with that technology. Below is a summary of the steps in this process:

1. Vehicles are assumed to start their service blocks with battery SOC at 90% of adjusted capacity. Our modeling is neutral with regard to the specific types of charging (fast or slow) that occur at garages to achieve this starting SOC.
2. Battery SOC declines based on distance traveled and the battery consumption rate.
3. If on-route charging is used, the battery's resulting SOC increase is calculated based on several factors:
    a. On-route charging may occur at the 13 locations selected to represent a "limited on-route charger network." These locations were selected to maximize potential charger utilization, especially by buses that would otherwise have a low SOC, without requiring excessive infrastructure investment. However, further analysis will be required to finalize the network of on-route charging locations and to identify the optimal number of chargers at each location.

[1] A vehicle block is an assignment of work for a single (non-specific) bus, outlining all trips, both revenue and non-revenue, and any recovery time between those trips. A vehicle block typically starts and ends at a garage, but some have alternate start/end locations.

b. Estimated layover time is determined by adjusting scheduled layover time according to the average percent of scheduled layover time buses experienced during actual operation at the end of the appropriate route, in the appropriate direction, at the appropriate time of day. This uses on-time performance data from eight weeks at various times in 2018.
c. Time with access to a charger is determined by adjusting estimated layover time based on the number of buses scheduled to be present at the charging location. If there are more buses than chargers, the charging access is assumed to be distributed equally.
d. Time spent charging is determined from the time with access to a charger by subtracting two minutes total for charger connection and disconnection.
e. The power level that a bus will accept from an on-route fast charger depends on the battery SOC. When the SOC is relatively high or low, the battery will accept a reduced portion of the charger's rated power level. Figure 2 shows the relationship between the power accepted from a charger and battery SOC. This graph was provided by CTA Bus Engineering based on observed performance of CTA's installed 450kW overhead pantograph fast-chargers.

4. At every scheduled timepoint, battery SOC is compared with the minimum reserve SOC (which is 20% of adjusted capacity) to confirm the SOC is acceptable.

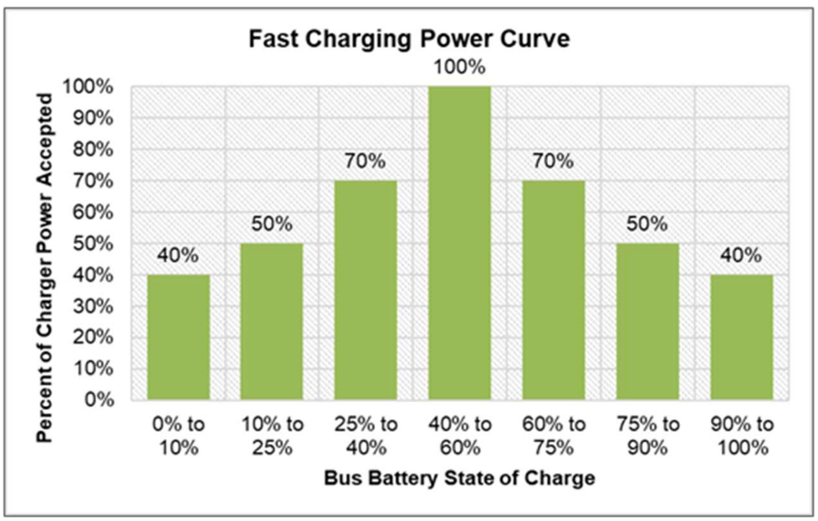


Figure 2 – Fast charger power accepted by a bus battery varies based on battery SOC.
Source: CTA Bus Engineering

A summary of the schedule modeling results is provided in the two tables below. This illustrates how schedule compatibility increases as technology improves. It also demonstrates the impacts of the different schedule characteristics between weekdays and Saturdays. Note that on Saturdays, vehicles tend to be assigned to operate significantly longer distances than on weekdays.

*Table 8 – Schedule compatibility results for **weekdays**, using the limited on-route charging network*

	Garage Charging is Sufficient	On-Route Charging is Required	Not Suitable to Electrify	Total Percent Compatible
Current Technology	51%	15%	34%	66%
Moderately Improved Technology	63%	14%	23%	77%
Significantly Improved Technology	78%	10%	12%	88%

*Table 9 – Schedule compatibility results for **Saturdays**, using the limited on-route charging network*

	Garage Charging is Sufficient	On-Route Charging is Required	Not Suitable to Electrify	Total Percent Compatible
Current Technology	7%	27%	66%	34%
Moderately Improved Technology	21%	30%	49%	51%
Significantly Improved Technology	43%	26%	30%	70%

C. Detailed Assumptions for Modeling of Garage Charging

A garage charging analysis was completed to compare the likely impacts of different potential charging strategies. The analysis considered how each bus in the system could be charged from its expected state of charge (SOC) at the end of its scheduled operations, to a target SOC that is required before starting its next assignment. Note that this analysis accounts for electrification of vehicle blocks that were shown to be incompatible with electric bus technologies,[2] and a small number of vehicle blocks do not require garage charging because on-route charging is sufficient, using results from the schedule modeling. Note also that this analysis focused on the "end state" of a fully electric fleet and did not explore the significant issues involved in the transition period during which garages would house both diesel and electric buses.

Table 10 – Bus SOC Assumptions for Garage Charging

Variable Description	Assumption	Source and Notes
Technology inputs	Moderate technology improvement	This was defined in Section B of this Appendix as part of schedule compatibility modeling.
On-route charger network	A limited on-route charger network with 13 locations	This was selected as the preferred on-route charger network.
Target battery state of charge (SOC) after garage charging	• 90% for most buses • 97% for buses at outdoor garages that are charged using fast charging only	The higher target SOC for outdoor buses that are charged using fast charging only serves to offset the 7% reduction in battery SOC that is anticipated in order to maintain battery temperature during outdoor storage in cold weather, while not connected to a charger.
Battery SOC of buses returning to the garage	Determined from schedule modeling for each vehicle block	The difference between this value and the target battery SOC represents the amount of charging that each vehicle block will require.

[2] The garage charging requirements of these vehicle blocks are unknown. There might be different amounts of charging needed depending on what changes are implemented to make the service compatible. Our solution to this is to assume similar characteristics to the service that was compatible for electrification with garage charging.

Our analysis tested several potential approaches to providing garage charging that achieves the target SOC. These approaches are summarized using the following three charging strategies with different mixtures of fast charging and slow charging. The assumptions regarding how these chargers would function are shown in Table 11.

- At one extreme, charging could be achieved with "**All Slow Charging**," defined as slow chargers available for all buses at a garage, in the locations where the buses are parked overnight. This would not require any fast chargers.[3]
- Next, a "**Moderate Fast Charging**" strategy would mean that existing fueling lanes are converted to offer one fast charger each; this allows every vehicle to fast-charge for a limited time during overnight servicing, similar to existing fueling operations. The vehicles that cannot reach their target SOC using fast charging during this time would be stored in parking lanes with slow chargers so they could charge sufficiently overnight.
- The third strategy, "**Mostly Fast Charging**," tested a greater amount of fast charging, with two more fast chargers installed at each garage in addition to the one fast charger per fueling lane included in the previous strategy. These additional fast chargers would prioritize buses that need a small amount of additional charging beyond what was possible using only existing servicing time. Note that our approach is agnostic to the specific configuration of additional fast chargers; they could be installed at locations aside from fueling lanes. A modest number of slow chargers would be provided to accommodate buses that cannot reach their target SOC using the fast chargers.

Table 11 – Charger Usage Assumptions for Garage Charging

Variable Description	Assumption	Notes
Operation of fast chargers matching existing fueling lanes	Each bus occupies a charger for 15 minutes	Source: CTA Bus Maintenance This approach mimics current fueling operations. One minute of the 15 would be spent connecting and disconnecting with the charger.
Operation of fast chargers in excess of existing fueling lanes	Prioritize buses closest to their target SOC	This approach maximizes charger utilization over an 8-hour charging period.
Power accepted from fast chargers	See Figure 2 in previous section.	Power accepted from fast chargers varies depending on the SOC of the bus charging.
Slow chargers required	Each slow charger has dispensers to serve three buses.	Buses that cannot sufficiently charge using fast chargers will use slow chargers.

[3] Note that in reality, at least one or two fast chargers would be desired as a failsafe, but these are excluded here for purposes of analysis.

Our analysis compared various characteristics of the charging strategies, in addition to the numbers of chargers required. We estimated the cost of the charger infrastructure and potential servicing labor; these assumptions can be found in the Cost Modeling section of this appendix. We also estimated each garage's peak power draw, assuming charging can be managed so the peak utilization is one-third less than it would be if all chargers were simultaneously running at full power. Finally, the additional space needed for slow charging infrastructure was estimated based on the assumptions in Table 12; at a typical garage the space needed was estimated in the range of 1 to 3 SBE.

Table 12 – Space Impact Assumptions for Garage Charging[4]

Variable Description	Assumption	Notes
Storage space reduction from each slow-charging bus stored outdoors	7 square feet	Source: CTA Bus Engineering. Space is used by gantry footings and the rows of electrical cabinets that must be positioned near charging dispensers. At indoor garages, we assume that gantry footings can be aligned with structural columns and will not contribute to the spatial impact.
Storage space reduction from each slow-charging bus stored indoors	6 square feet	
Space for one standard bus equivalent (SBE)	791 square feet	Used to convert spatial impacts into storage capacity impacts. Includes space for travel lanes and walkways between buses.

[4] While these values suggest a relatively small footprint, it will not always be possible to place equipment in a compact consolidated way that minimizes storage impacts. As a result, bus storage capacity lost could be greater than our estimates if equipment needs are spread throughout the storage area. Note that many of CTA's garages may have some unused space that could be repurposed to house charger equipment, but to be conservative we are not considering that in our space estimates. We assume no storage space reduction with fast charging space on the basis that several fast chargers can fit within the garage space currently occupied by fueling islands.

D. Detailed Assumptions and Inputs for Fleet Electrification Cost Modeling

Table 13 – Overall Assumptions

Variable Description	Value	Source and Notes
Inflation rate	1.8% annually	Producer Price Index & CTA Finance
Annual miles operated	34,000 per bus	CTA Bus Engineering

Table 14 – Diesel Fuel Cost Inputs

Variable Description	Value	Source and Notes
Diesel bus fuel consumption	• 3.590 miles per gallon (mpg) for a 40 ft bus • 2.435 mpg for a 60 ft bus	CTA Transit Asset Management. Note that this does not account for potential improvement over time; we similarly do not account for electric bus energy consumption rates improving over time.
Hybrid bus fuel consumption	3.463 mpg for a 60 ft bus	
Diesel fuel price	$2.53 per gallon	CTA Finance. Future diesel prices will follow US Energy Information Administration (EIA) projections for Transportation Diesel Fuel (distillate fuel oil).
Annual cost of diesel auxiliary heating	• $44 per indoor-stored bus • $261 per outdoor-stored bus that is connected to a slow charger overnight • $523 per outdoor-stored bus that is *not* connected to a slow charger overnight	CTA Bus Engineering. Calculated based on CTA's existing diesel auxiliary heater specifications, including diesel consumption rates and temperature setpoints.

Table 15 - Electricity Cost Inputs

Variable Description	Value	Source and Notes
Electric bus electricity consumption rate	• 2.8 kWh/mi for a 40 ft bus • 3.5 kWh/mi for a 60 ft bus	Average of values observed for adverse conditions and ideal conditions. Note that different battery consumption rate inputs are used in the schedule modeling when seeking to represent adverse winter conditions to represent year-round reliably achievable performance.
Electricity pricing	Typically between 7 and 9 cents per kWh.	Calculated based on based on CTA's current electricity supply pricing and electric utility rates, including variable demand (kW) charges. Future pricing will apply growth based on EIA projections for Transportation Electricity.

Table 16 – Bus Maintenance Cost Inputs

Variable Description	Value	Source and Notes
Annual maintenance cost per mile operated	Inputs for diesel (including diesel hybrid) buses and electric buses are shown in the graph below.	Inputs vary based on bus age. The graph below shows a projection by CTA Bus Engineering.
Mid-life overhaul cost	• $150,000 for diesel/hybrid bus • $350,000 for electric bus	CTA Bus Engineering

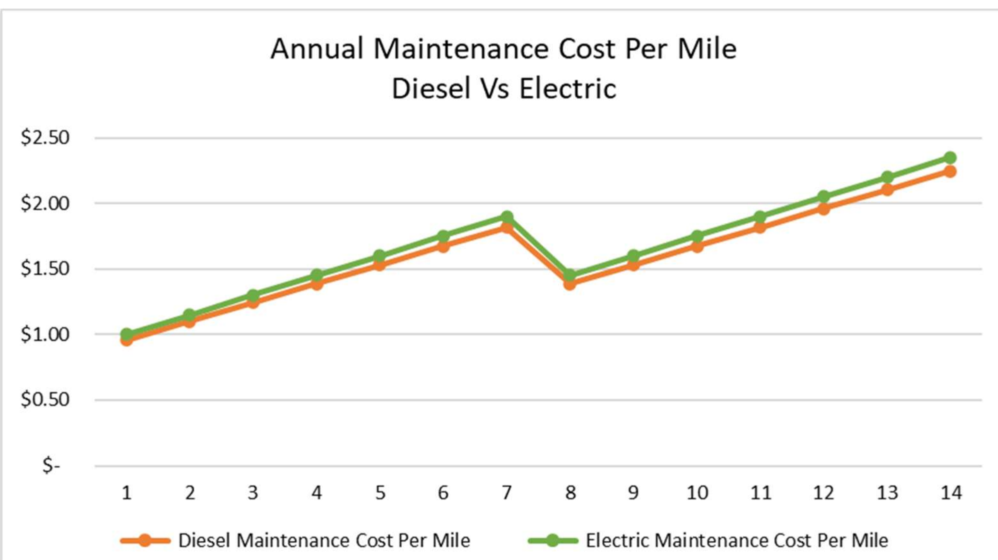


Figure 3 – Annual maintenance cost per mile inputs for diesel and electric buses

Table 17 - Electric Bus Charging Infrastructure Maintenance Cost Inputs

Variable Description	Value	Source and Notes
Slow charger annual maintenance	• 24 hrs labor per unit • $1,200 for material per unit	CTA Bus Engineering
Fast charger annual maintenance	• 72 hrs labor per unit • $11,500 for material per unit	CTA Bus Engineering
New substation annual maintenance	• 480 hrs labor per unit • $5,900 for material per unit	CTA Infrastructure, based on current substation annual material budget.
Fully-loaded cost per hour for electricians	$87.85 per hour	CTA Infrastructure
Note that this category has a 15% contingency included on material and a 20% contingency included on labor. This reflects industry best practice to cover an array of possible costs such as additional maintenance of fire life safety systems, heating, or HVAC systems.		

Table 18 – Bus Schedule Change Cost Inputs

Variable Description	Value	Source and Notes
Fully-loaded cost per hour for bus operations	$82.62 per hour	This rate is applied to the bus operator labor associated with splitting apart long vehicle blocks as needed to ensure compatibility with electrification. This added labor cost is incorporated into the cost modeling in the later years of the transition period as schedule changes become necessary to continue fleet electrification.

Table 19 – Charging Labor Cost Inputs

Variable Description	Value	Source and Notes
Fully-loaded cost per labor hour for Bus Servicers	$49.35 per hour	This rate is applied to the *added* time spent in a fueling lane for fast charging, beyond current servicing time.

Table 20 – Garage Facility Upgrade Cost Inputs

This category includes estimates of facility improvements that will be necessary to bring bus facilities into a state of good repair. Not all of these investments are necessary to support electrification, however; more detailed facility-specific studies will be required to clarify the specifics of required electrification-related facility upgrades. (The studies themselves should be considered part of these costs.) Some of the facility costs may be essential to address at the time of electrification, and others may be convenient/cost-effective to address at the time of electrification.

Variable Description	Value	Source and Notes
State of good repair improvements for Chicago, 103rd Street, 74th Street, and Kedzie	$100 million for each garage	CTA Infrastructure and Facilities. This may include roof repairs to prevent water damage to installed chargers, paving repairs concurrent with installation of gantry foundations, or other code compliance upgrades identified through construction permitting processes.
Full replacement of 77th Street & South Shops Bus Shops Heavy Maintenance	$630 million	CTA Infrastructure and Facilities
New garage facility, including land	$450 million	CTA Infrastructure and Facilities
Potential upgrades for Forest Glen	• Full replacement as outdoor garage for $335 million • Full replacement as outdoor garage with reconfiguration (adding 101 SBE) for $399 million • Full replacement as indoor garage for $450 million	CTA Infrastructure and Facilities
Potential upgrades for North Park	• Full replacement as outdoor garage for $335 million • Full replacement as outdoor garage with reconfiguration (adding 40 SBE) for $360 million • Full replacement as indoor garage for $450 million	CTA Infrastructure and Facilities

Table 21 – Bus Purchase Cost Inputs

Variable Description	Value	Source and Notes
Bus lifetime	14 years	Analysis Plan
Electric bus purchase prices	• $1 million for a 40 ft bus • $1.5 million for a 60 ft bus	CTA internal budgeting values from CTA Bus Engineering. Future electric bus purchase price trends are assumed to follow average California Air Resources Board (CARB) projections.
Diesel bus purchase prices	• $656,000 for a 40 ft bus • $1.018 million for a 60 ft bus	CTA internal budgeting values from CTA Bus Engineering. Future diesel and hybrid bus purchase price trends are assumed to increase $17,900 annually based on the average trend of new bus deliveries reported in the APTA Fact Book.
Hybrid bus purchase prices	• $906,000 for a 40 ft bus • $1.268 million for a 60 ft bus	
After-market features	$11,580 per bus that increases the fleet size	CTA Revenue and Fare Systems. Includes farebox and Ventra mobile validator.

Table 22 – Electric Bus Charger Infrastructure Cost Inputs

Variable Description	Value	Source and Notes
Fast chargers at garages	$1.75 million per charger	Based on CTA experience with chargers at Chicago Garage. Includes materials, design, labor, liabilities, and installation. Value also includes all infrastructure needed between the switchgear and the charger, including conduit, cabling, design, construction management, and CTA management costs. The same cost is used for fast charger replacements.
Slow chargers	$652,000 per slow-charging bus	Based on manufacturer quotes and estimates from CTA Bus Engineering. Includes charger, dispenser, gantry to support slow chargers, delivery, installation, conduit, foundations, ventilation, and other soft costs. We assume that, in both indoor and outdoor facilities, slow chargers are suspended by overhead gantry on dedicated supports.
Slow charger replacements	$126,000 per bus	Includes old equipment removal, new equipment installation, and soft costs, and excludes one-time investments such as gantry and conduit.
On-route fast charger installations	$3,472,000 per location plus $2,267,000 per charger	Extrapolated based on actual costs from CTA's on-route charger installations at Chicago/Austin and Navy Pier, including construction and electrical infrastructure.
Charger lifetime	14 years	Matches bus lifetime
Note that costs in this category have a 40% contingency included; this reflects industry best practice to cover an array of risks at an early phase of project development. For example, the contingency may cover items such as diesel fuel tank decommissioning and fire safety upgrades.		

Table 23 – Garage Electrical Upgrade Cost Inputs

Variable Description	Value	Source and Notes
ComEd electrical upgrade costs	Typical values range from $4 million to $8 million per garage	ComEd provided estimates for potential electrical capacity upgrades up to the 10 MW level; we include the Rider DE Deposit and On-Property Costs and scale to each facility's modeled total power demand.
Back-up power source	$2.8 million per garage	Based on CTA estimates for an on-site energy storage system. This serves to represent a range of resiliency solutions that could be considered at garages.
Switchgear	$504,000 per 2.5 MW of capacity	Based on past CTA charging station and substation projects.
Construction costs of garage electrical upgrades	$15.476 million per garage	Based on past CTA charging station and substation projects.
Note that costs in this category have a 40% contingency included; this reflects industry best practice to cover an array of risks at an early phase of project development. For example, the contingency may cover items such as code-required upgrades.		

Table 24 – Emissions Inputs

Variable Description	Value	Source and Notes
CO_2 emissions rate for diesel/hybrid buses	10.21 kg CO_2 per gallon diesel + 5.5929 g CO_2e per gallon diesel	2018 USEPA Emission Factors for Greenhouse Gas Inventories
NO_x emissions rate for diesel/hybrid buses	16.64 g NO_x per mile	California Air Resources Board
$PM_{2.5}$ emissions rate for diesel/hybrid buses	Declines over time from 0.089 g per mile in 2022 to 0.038 g per mile in 2030	EPA Estimated U.S. Average Vehicle Emissions Rates per Vehicle by Vehicle Type Using Gasoline and Diesel, 2020
CO_2e emissions rate from power generation	452.6 g CO_2e per kWh	This combines the 2020 generation fuel mix of PJM with emissions rates from Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model. We assume that PJM's trend of declining CO_2e emissions rates (2.6% annually) will continue per the 2020 PJM Emissions Rate Report.
NO_x emissions rate from power generation	0.21635 g NO_x per kWh	This combines the 2020 generation fuel mix of PJM with emissions rates from the GREET Model. We assume that PJM's trend of declining NO_x emissions rates (5.7% annually) will continue per the 2020 PJM Emissions Rate Report.
$PM_{2.5}$ emissions rate from power generation	0.01757 g $PM_{2.5}$ per kWh	This combines the 2020 generation fuel mix of PJM with emissions rates from the GREET Model.